Co-Designing Accessible Technologies: A Research Through Design Approach to Modern 2D Tactile Displays

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Abstract

Two-dimensional (2D) refreshable tactile displays represent a promising assistive technology for individuals who are Blind or have Low Vision (BLV), offering interactive access to complex materials commonly used in science, technology, engineering, and mathematics (STEM). These devices have the potential to enhance access to structured digital content, such as documents and visualizations in the form of graphs, and diagrams. However, the lack of standardized interaction paradigms and design guidelines for tactile user interfaces (TUIs) significantly limits their usability. Furthermore, the limited involvement of individuals who are BLV in the design process of such devices often results in a misalignment between user needs and designers' assumptions.

This thesis adopts a Research through Design (RtD) approach for developing modern 2D refreshable tactile displays, with a strong emphasis on integrating user feedback throughout the whole design process. The research addresses the software, hardware, and ergonomic aspects of the display. For this purpose, four TUIs were developed through this work to support the exploration of STEM-related content. Additionally, techniques for segmenting and representing complex document layouts, such as multi-column research papers, were implemented using machine learning models, while novel interaction concepts were designed to support efficient tactile navigation. In parallel, vector-based graphical formats were incorporated to improve access to graphs and technical diagrams, and overcome the low-resolution problem commonly associated with such devices.

A functional prototype was developed featuring a custom file management TUI, allowing users to access and organize files independently, without relying on external devices. To ensure the physical design of the device reflected user needs, a new low-fidelity (lo-fi) prototyping methodology was introduced, specifically tailored for participants who are BLV. This approach facilitated active involvement in early hardware design process and was followed by iterative refinement, resulting in a high-fidelity (hi-fi) prototype optimized for STEM applications. The designed device was evaluated through a series of user studies with nine blind participants, focusing on usability, learnability, and user satisfaction. Findings show that the developed device can support effective and efficient access to complex STEM materials and that the participants expressed high levels of satisfaction with the possibilities offered by the device.

In addition to the technical contributions, this thesis introduces a structured co-design process, including a workshop format and strategies for the meaningful involvement of participants who are BLV. It also offers practical guidelines for designing the software component of such devices, informed by insights from user studies, participatory design sessions, and iterative prototyping. Overall, this research presents a holistic, user-centered framework for developing modern 2D refreshable tactile displays and TUIs, demonstrating that involving individuals who are BLV throughout the design process can lead to creating relevant assistive technologies which can assist users who are BLV and meet their needs and expectations.

Kurzfassung

Zweidimensionale (2D) dynamische taktile Displays stellen eine vielversprechende assistive Technologie für blinde und sehbehinderte Personen (BSB) dar, da sie einen interaktiven Zugang zu komplexen Materialien ermöglichen, die häufig in den Bereichen Wissenschaft, Technologie, Ingenieurwesen und Mathematik (MINT) verwendet werden. Diese Geräte haben das Potenzial, den Zugang zu strukturierten digitalen Inhalten wie Dokumenten und Visualisierungen in Form von Grafiken und Diagrammen zu verbessern. Allerdings schränkt das Fehlen standardisierter Interaktionsparadigmen und Gestaltungsrichtlinien für taktile Benutzeroberflächen (TUIs) ihre Nutzbarkeit erheblich ein. Zudem führt die begrenzte Einbeziehung von Personen, die BSB sind, in den Gestaltungsprozess solcher Geräte häufig zu einer Diskrepanz zwischen den tatsächlichen Nutzerbedürfnissen und den Annahmen der Designer*innen.

Diese Dissertation verfolgt einen „Research through Design“ (RtD)-Ansatz zur Entwicklung moderner 2D dynamischer taktiler Displays mit einem starken Fokus auf die Integration von Nutzerfeedback während des gesamten Designprozesses. Die Forschung befasst sich mit den softwaretechnischen, hardwareseitigen und ergonomischen Aspekten des Displays. Zu diesem Zweck wurden im Rahmen dieser Arbeit vier TUIs entwickelt, die die Erkundung von MINT-Inhalten unterstützen. Zudem wurden Techniken zur Segmentierung und Darstellung komplexer Dokumentlayouts, etwa von wissenschaftlichen Artikeln mit mehreren Spalten, unter Einsatz von Machine-Learning-Modellen umgesetzt. Neue Interaktionskonzepte wurden entworfen, um eine effiziente taktile Navigation zu ermöglichen. Parallel dazu wurden vektorbasierte Grafikformate integriert, um den Zugang zu Diagrammen und technischen Zeichnungen zu verbessern und das häufig auftretende Problem der niedrigen Auflösung solcher Geräte zu überwinden.

Ein funktionsfähiger Prototyp wurde entwickelt, der über eine eigene TUI zur Dateiverwaltung verfügt und es Nutzenden ermöglicht, unabhängig und ohne externe Geräte auf Dateien zuzugreifen und diese zu organisieren. Um sicherzustellen, dass das physische Design des Geräts den Bedürfnissen der Nutzer*innen entspricht, wurde eine neue Methode für Low-Fidelity-(Lo-Fi)-Prototyping eingeführt, die speziell auf BSB-Teilnehmende zugeschnitten ist. Dieser Ansatz ermöglichte eine aktive Mitwirkung im frühen Hardware-Designprozess und wurde durch iterative Verfeinerung ergänzt, was schließlich zu einem High-Fidelity-(Hi-Fi)-Prototyp führte, der für MINT-Anwendungen optimiert ist. Das entwickelte Gerät wurde in einer Reihe von Nutzungsstudien mit neun blinden Teilnehmenden evaluiert, wobei der Fokus auf Nutzbarkeit, Erlernbarkeit und Nutzerzufriedenheit lag. Die Ergebnisse zeigen, dass das entwickelte Gerät einen effektiven und effizienten Zugang zu komplexen MINT-Inhalten unterstützt und dass die Teilnehmenden ein hohes Maß an Zufriedenheit mit den angebotenen Möglichkeiten äußerten.

Neben den technischen Beiträgen stellt diese Dissertation einen strukturierten Co-Design-Prozess vor, der ein Workshop-Format sowie Strategien zur sinnvollen Einbeziehung von BSB-Teilnehmenden beinhaltet. Darüber hinaus werden praktische Richtlinien für die Gestaltung der Softwarekomponenten solcher Geräte angeboten, die auf Erkenntnissen aus Nutzungsstudien, partizipativen Design-Sitzungen und iterativen Prototyping-Phasen basieren. Insgesamt präsentiert diese Forschung einen ganzheitlichen, nutzerzentrierten Rahmen für die Entwicklung moderner 2D dynamischer taktiler Displays und TUIs und zeigt, dass die kontinuierliche Einbindung von Personen, die BSB sind, im Designprozess zur Entwicklung relevanter assistiver Technologien führen kann, die die Nutzer*innen unterstützen und ihren Bedürfnissen und Erwartungen gerecht werden.

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Sara Zalabany

Contents

Acronyms and Definitions

Acronyms

API	Application Programming Interface
BLV	Blind or Have Low Vision
CSS	Cascading Style Sheet
CNN	Convolutional Neural Network
DAISY	Digital Accessible Information System
DLA	Document Layout Analysis
DXF	Drawing Exchange Format
EPS	Encapsulated PostScript
EPUB	Electronic Publication
FSH	Filesystem Hierarchy
GraVVITAS	Graphics Viewer using Vibration, Interactive Touch, Audio, and Speech
GUI	Graphical User Interface
HCI	Human Computer Interaction
ICD	International Statistical Classification of Diseases and Related Health Problems
MIDI	Musical Instrument Digital Interface
MVC	Model View Controller
NASA – TLX	Nasa Task Load Index
OCR	Optical Character Recognition
RtD	Research through Design
SDK	Software Development Kit
STEM	Science, Technology, Engineering, and Mathematics
SUS	System Usability Scale
SVG	Scalable Vector Graphics
SVGT	Scalable Vector Graphics Tiny
SMA	Shape Memory Alloys
SMP	Shape Memory Polymers

Taxels	Tactile Pixels
TTS	Text-to-speech Synthesizer
TUI	Tactile User Interface
UML	Unified Modeling Language
UI	User Interface
WCAG	Web Content Accessibility Guidelines
W3C	World Wide Web Consortium
XHTML	eXtensible HyperText Markup Language
YOLO	You Only Look Once
1D	One Dimensional
2D	Two Dimensional
3D	Three Dimensional

1 Introduction

Information accessibility continues to pose challenges for individuals who are BLV, and it becomes evident in domains where spatial layout and graphical content are central to improving the understanding, such as STEM fields [1, 2]. While assistive technologies, such as screen readers and one-line Braille displays provide access to information, they are limited in supporting spatial exploration and access to graphical information in their original format. Other traditional methods that aim to overcome these problems rely on the use of tactile materials produced using physical means, such as embossed or swell paper. These methods can represent static diagrams, maps, or charts, and are commonly used in educational contexts. However, they are often time-consuming to produce, expensive to distribute, and inflexible, meaning that any change in the source material requires an entirely new tactile material. Additionally, such representations are limited to pre-defined content and lack interactivity.

Recent advances in hardware have introduced 2D refreshable tactile displays, which present a promising alternative [3]. These displays use arrays of movable pins to present information in a tactile manner that can be updated dynamically, enabling access to spatial information such as layouts and graphics in real time. These devices can offer greater flexibility and responsiveness in comparison to embossed papers. However, their potential remains largely unrealized due to gaps in designing software solutions, limited application support, and a lack of comprehensive guidelines for tactile user interaction [4].

Another limitation in the development of these technologies is the insufficient involvement of users who are BLV in the design process. Many devices are created based on assumptions made by sighted designers or with only minimal user feedback, often through short usability testing sessions at the end of development [4]. This approach overlooks the expertise of individuals who are BLV as active contributors and fails to account for the diverse strategies and preferences they use to access digital information.

This dissertation addresses these challenges through a RtD approach that centers the input of participants who are BLV throughout the design and development of 2D refreshable tactile displays. It begins by investigating how the software for such devices can be designed to support document layout and graphical exploration in an accessible, effective, and intuitive manner.

To support early-stage involvement of participants who are BLV, the research introduces a novel lo-fi prototyping method which makes it possible to co-design 2D tactile displays without requiring complex fabrication or fully functioning hardware. In parallel, a hi-fi prototype of a portable 2D tactile display is developed, integrating hardware and software designed in collaboration with users who are BLV. The prototype includes four TUIs designed to support exploration and interaction with commonly used STEM content.

Through these contributions, the dissertation offers new insights and practical tools for designing modern tactile technologies that support independent access to spatially rich content used in STEM fields. It emphasizes the importance of participatory and co-design approaches in assistive technology development and argues for the integration of individuals who are BLV not merely as testers, but as designers in the creation of future accessibility solutions.

1.1 Motivation

There are around 43 million people were blind globally in 2020 [5]. For them, accessing digital content, especially in STEM fields, remains a significant challenge. Screen readers and one-line tactile displays are commonly used tools for accessing such information by individuals who are BLV. While screen readers provide sequential audio output and one-line Braille displays allow tactile reading of text, these approaches offer limited access to spatial structure and visual elements. Layout information, such as the relative size and position of components, plays a key role in supporting comprehension and navigation for sighted readers [6, 7, 8, 9]. However, this information is often lost when content is reduced to a linear format.

Additionally, visualizations commonly used in STEM fields frequently depend on interpreting symbols, shapes, and spatial relationships. These graphical elements cannot be conveyed through speech or Braille text alone. Tactile graphics produced via embossing or swell paper offer an alternative, but they are static, time-consuming to create, and not suitable for dynamic or interactive content. This lack of access to rich, multimodal content contributes to the exclusion of blind users in educational and professional contexts [1]. It limits their ability to explore materials independently, particularly when content relies heavily on spatial organization or visual detail.

2D tactile displays offer a promising solution, in comparison to static tactile graphics, as they can offer dynamic and interactive feedback that allows users to explore content through touch in real time. With growing interest in these displays among blind users [3], there is a need for well-designed tactile interfaces, specifically for such devices and addressing the problem of involving individuals who are BLV only at the evaluation stage, which limits the relevance of resulting designs [4].

Hardware design has also seen limited user involvement. Devices are frequently developed without input from users who are BLV, leading to designs that may be difficult to operate independently or unsuited to everyday environments such as classrooms. Factors like portability, ergonomics, and interface layout are often overlooked. Therefore, the design of 2D tactile displays-related software and hardware, remains underexplored. This dissertation addresses this gap by advancing methods for co-designing software and hardware with users who are BLV. It aims to support independent, efficient interaction with tactile content by embedding user perspectives into all stages of development.

1.2 Research Objectives

This dissertation investigates the design and development of 2D refreshable tactile displays to improve the access to information in STEM domains for individuals who are BLV. The research adopts a co-design approach that actively involves participants who are BLV in shaping both the hardware and software components of the display from the earliest stages of the process. Therefore, this thesis addresses the following research questions:

1. How can TUIs be designed to provide effective access to STEM content on 2D tactile displays?
2. How can users who are BLV be meaningfully involved in the design of the hardware of 2D tactile displays?
3. What design features and interaction concepts should a 2D tactile display incorporate to support independent access to digital content for users who are BLV?

To address these questions, the dissertation introduces the following technical and methodological contributions:

1. The design and implementation of four examples of TUIs, designed specifically for 2D refreshable tactile displays, developed based on the suggestions of participants who are BLV and actively involved throughout the design process.

2. A novel lo-fi prototyping method adapted to the needs of individuals who are BLV. The method enables collaborative design of tactile devices by providing accessible materials and structured facilitation techniques that support active participation in design workshops.
3. The creation of a functional hi-fi portable prototype of a 2D refreshable tactile display, which includes a custom file system and a three TUIs designed for reading and exploring STEM content.

Taken together, these contributions aim to advance the state of the art in designing 2D tactile displays to support independent access to STEM materials. Furthermore, the work contributes to the development of inclusive design methodologies for involving individuals who are BLV.

The following section outlines the structure of the dissertation and provides an overview of the content of each chapter.

1.3 Structure of the Dissertation

This dissertation is structured as follows:

- **Chapter 2. Background** This chapter provides foundational context for the dissertation. It begins by introducing key information about individuals who are BLV, highlighting their diverse working methods and the tools they commonly use to access information. It then presents the concept of haptic perception and the role of touch in acquiring information, with a particular emphasis on how users who are BLV interpret tactile stimuli. The chapter reviews the various tactile materials and techniques currently employed in STEM contexts, including embossed graphics, 3D-printed materials, alongside commonly used assistive technologies such as screen readers and one-line Braille displays and examines their respective strengths and limitations. The chapter then presents a survey of recent research efforts aimed at addressing these challenges, including novel rendering techniques, and interaction concepts. The chapter concludes by reviewing the emergence of 2D refreshable tactile displays, the TUIs developed for them, identifying gaps in both the hardware and software design processes.
- **Chapter 3. Tactile User Interfaces for Accessing Digital Documents and Graphics** This chapter details the design and implementation of three TUIs developed for 2D refreshable tactile displays. The first two interfaces are designed to support access to complex document formats, such as multi-column documents. These interfaces enable navigation through multi-page content, exploration of structured layouts, and access to metadata like titles, headings, and figure captions through both touch and audio feedback. The third interface introduces a novel method for presenting technical diagrams used in STEM education. This interface utilizes vector-based representations such as SVG-formatted graphics to maintain the spatial and structural properties of diagrams while supporting interactivity through tactile exploration. The design choices, user interaction concepts, and accessibility considerations are discussed in depth, along with the technical architecture and implementation details of the TUIs, as well as the evaluations results of testing these interfaces with individuals who are BLV.
- **Chapter 4. Designing a Low-Fidelity Prototyping Method for Co-Designing 2D Tactile Displays** This chapter presents a novel approach to adapting lo-fi prototyping for co-designing with users who are BLV. Traditional design methods often rely on visual materials, which are not directly accessible to blind participants. The adapted method described in this chapter addresses this barrier by introducing accessible materials, tools, and facilitation techniques that enable users who are BLV to contribute actively in design workshops. The methodology supports the structured creation and evaluation of prototype concepts for 2D tactile displays. It also highlights strategies for fostering collaboration between blind participants, and discusses how participants' contributions shaped the prototyping process and influenced both software and

hardware design directions. The chapter concludes with a set of suggestions for structuring and conducting design workshops that support collaborative work between blind participants and discusses the role of sighted assistants in such workshops.

- **Chapter 5. Design and Development of a Portable 2D Tactile Display** This chapter describes the design and development of a portable, hi-fi prototype of a 2D refreshable tactile display. It includes an overview of the hardware design, including the input methods, and connectivity features. The chapter also presents the design of a custom file system for 2D tactile displays that allows the users to independently manage and store their files on the device. Three core applications are introduced: a text viewer, a document reader, and a graphics viewer, each designed to support multimodal interaction through touch, buttons, and audio feedback. Considerations around ergonomics, portability, and usability are also discussed. This prototype reflects the culmination of the co-design process and aims to serve as a platform for further research and development in tactile displays technologies. Finally, the chapter presents an evaluation of the developed device, along with users' feedback and suggestions for potential future features.

2 Background

This chapter provides an overview of the fundamental concepts relevant to the research objectives of this dissertation. It begins by introducing the end users of this work, individuals who are BLV, and clarifies the distinction between blindness and visual impairment (Section 2.1) and the implications of these differences on the methods of working of each group and the corresponding assistive tools and methods used by each group for accessing information. Additionally, the introduction highlights the differences that need to be considered when designing systems for each group. Section 2.3 explores the various types of tactile media used by individuals who are BLV, offering insight into their specific needs. It further reviews existing assistive technologies, ranging from traditional tools, such as screen readers to physical media like embossed paper and 3D-printed materials, concluding with 2D tactile displays, which is the central focus of this dissertation. Finally, Section 2.7 discusses previous research efforts on designing TUIs for 2D tactile displays.

2.1 Blindness and Low Vision

Vision levels can vary significantly from person to person. The degree of visual impairment is typically defined based on several factors, including visual acuity, visual field, and the ability to perceive color and contrast. These dimensions influence how individuals experience their environment and determine the classification of their condition, ranging from low vision to total blindness. The visual impairment definitions used in this dissertation are based on the definitions of the World Health Organization (WHO) [10].

According to the International Statistical Classification of Diseases and Related Health Problems (ICD) system [11], released in 2024 by the WHO, visual impairment can be classified into two main categories, low vision and blindness depending on the visual acuity level. The visual acuity means the ability of the eyes to realize details [10]. The system defines a visual acuity between 6/18 and 3/60 to be considered as mild to severe visual impairment, while blindness is defined as a visual acuity level worse than 3/60.

A blind person is defined by the WHO as someone who has little to no residual vision and therefore has to rely on other methods to substitute the vision skills using other senses such as touch for interacting and manipulating objects, Braille for reading and canes or dogs for mobility [11]. However the definition from WHO differs for low vision individuals, such that a low vision individual is defined as someone who has significantly reduced vision in the better eye (6/18 vision acuity or 20 degrees diameter visual field) after treatment or using refractive correction. However, a low vision individual can still employ their reduced vision for learning, planning and performing tasks that require vision [10, 12].

From these definitions, it is to be noted that blind individuals can differ from low vision individuals on the senses used for working and accessing information, as low-vision individuals can still rely on vision skills. Therefore, the strategies and resources for perceiving information differ for each target group. These classifications are critical when designing accessible technologies, as the needs and interaction strategies of users who are blind differ from those of users with low vision. For instance, individuals with low-vision might rely on screen magnifiers, high-contrast settings, or large text, whereas blind users typically depend on screen readers, audio feedback, and tactile interfaces. Furthermore, contrast sensitivity and color perception issues may affect the ability to interpret visual cues, such as distinguishing text from background or recognizing color-coded information. The next section explains the different working methods of individuals who are BLV and presents the concept of accessibility.

2.2 Haptic Perception as a Sensory Modality for Information Access

Humans explore and make sense of their surroundings through a combination of sensory modalities which are vision, hearing, smell, taste, and touch. Among these, the sense of touch plays a crucial role in perceiving the physical properties of objects and navigating the immediate environment. For individuals who are BLV, hearing and touch become the primary non-visual channels for accessing and interpreting information [13]. This process known as haptic perception, refers to the ability to perceive and interpret information through touch. The term haptic originates from the Greek word haptikos, derived from haptesthai, meaning "to grasp, touch, or perceive".

Haptic perception involves two main components, tactile (or cutaneous) and kinesthetic sensing [14]. Tactile sensing refers to the detection of stimuli through the receptors located on the surface of the skin, enabling the perception of texture, temperature and pressure. In contrast, kinesthetic sensing involves proprioceptive feedback from muscles, tendons, and joints, allowing individuals to recognize the position and movement of their limbs [15].

Haptic perception can further be distinguished by the mode of interaction, specifically between active and passive touch. In active touch, as explained by [16], the individual deliberately explores an object or surface through purposeful hand or body movements, such as tracing a shape or feeling a texture. This form of touch engages both tactile and kinesthetic sensing and allows for greater control and information acquisition. In contrast, passive touch occurs when tactile stimuli are applied to a stationary body part without voluntary movement, such as when a textured surface is pressed against the skin.

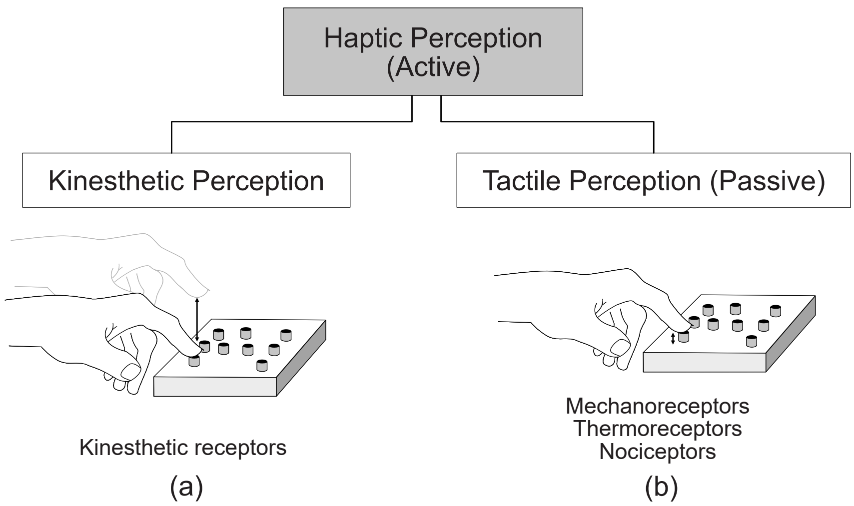


Figure 2.1: The definition and components of haptic perception: (a) kinesthetic perception, and (b) tactile perception.

In previous research, passive and active exploration have been explored and compared by researchers. It was noticed that passive exploration is often used when teaching new skills to individuals, while the active exploration is often favored for allowing users to distinguish between objects and understanding attributes such as shapes, hardness and texture [17, 15]. An example of this is the work of Gibson [16], where active touch was shown to be more effective for tasks involving spatial interpretation and object recognition, where participants in his experiment showed better understanding of 2D shapes when they used their hands to explore cookie cutters, activating the kinesthetic receptors. In comparison, the participants performed worse when they depended on the passive touch by placing the cutters in their hand without performing hand movements. This was also confirmed by Rodriguez et al. [17], which showed that active exploration can enable better shape recognition, while passive exploration is better suited for navigation through complex and simple pathways.

2.3 Information Access for Individuals Who are Blind or Have Low Vision

Accessibility means providing people with disabilities the same opportunity to access and engage with information as those without disabilities. For individuals who are BLV, this includes gaining equal access to documents, images, and user interfaces. As digital platforms continue to evolve, addressing the accessibility of digital information is not only a matter of inclusion but also a prerequisite for equitable participation in the digital world.

Accessibility becomes particularly critical in STEM fields, where students who are BLV and professionals often face significant challenges [2]. These challenges are largely due to the visually complex nature of STEM materials, which often rely on graphics such as charts, diagrams, and mathematical visualizations [18]. While descriptive approaches, such as alternative text or text-based explanations, help to some extent, they rarely provide the full experience or enable independent exploration. Personal access to graphical content remains essential for understanding and engaging with such material on a deeper level.

Technical diagrams, such as flowcharts, line graphs, chemical structures, and electrical circuits, play a central role in STEM communication and learning. However, these materials are often inaccessible or only partially accessible using current assistive technologies [19]. These digital barriers can significantly hinder the inclusion and success of individuals who are BLV in education and professional settings [20].

Previous research explored various methods for making digital information accessible to individuals who are BLV, addressing the challenges posed by traditional formats like printed text and static images. One common approach is based on haptic perception, utilizing physical representations of information. These representations can be created through different techniques, including Braille embossers, swell paper, 3D printing, or laser-cutting materials such as wood. Such tactile formats have found applications across multiple use cases, such as tactile maps for navigation, diagrams and graphics in STEM, and accessible books or documents. These methods allow individuals who are BLV to interact with and explore information in a tangible way, facilitating access to both educational and practical content.

Other methods involve audio, where screen readers convert digital text into speech, enabling individuals who are BLV to access textual information in a linear manner. These methods are widely used, particularly for documents that are primarily text-based. However, there have been efforts in using the same concept for representing graphical information, as well as web content. In addition, researchers have explored hybrid approaches that combine tactile and audio feedback [21, 22, 23, 24, 25]. These multimodal representations provide a more interactive experience, enabling individuals who are BLV to both hear and feel the content, offering a richer means of interaction.

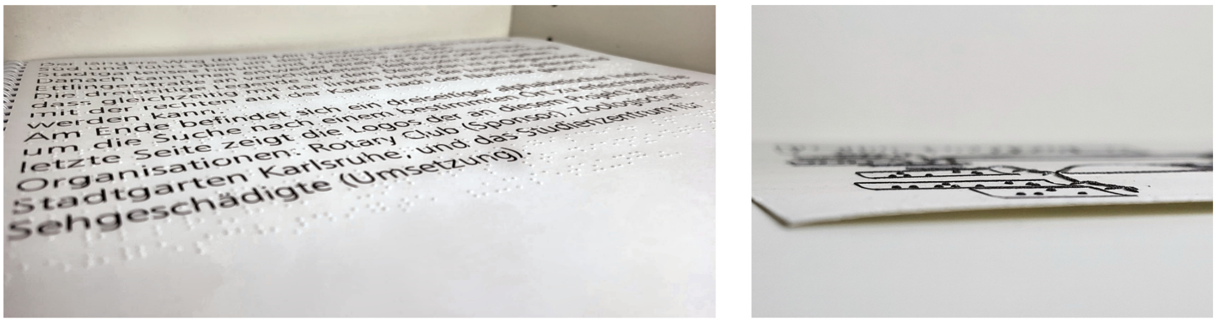
In recent years, there has been a shift toward more dynamic, interactive solutions, such as mobile apps and 2D refreshable tactile displays. These devices aim to provide a more engaging user experience by allowing real-time interaction with both textual and graphical content. 2D tactile displays, in particular, can adapt to different layouts, enabling users to explore documents, diagrams, and other graphical materials. These advancements play a crucial role in expanding access to digital information across various domains, including education, professional settings, and everyday life.

The following sections delve deeper into these methods, exploring the research and developments aimed at enhancing information accessibility for individuals who are BLV.

2.4 Physical Representations Using Tactile Materials

Physical representations have been widely used to provide individuals who are BLV with access to information. The advantage of such methods is the ability to offer a quite similar format to the original information by printing the information on papers or other physical materials, which can be explored through touch. These representations aim to provide individuals who are BLV access to structure, spatial relationships, and layout elements that are difficult or impossible to fully convey using audio or textual descriptions alone. There exists multiple methods for creating such physical representations of the data. The most common format depends on the use of papers which can be produced by different printing technologies. One method is embossed papers which can be generated by a printer called an embosser. In the embossing process, papers are punched to create dots, as shown in Figure 2.2 (a), that can be later felt by the person using touch senses. However, the durability of the dots or holes is liable to be destroyed after multiple uses.

Another common method depends on the use of microcapsule papers, or what is also known as puff, capsule or swell paper, shown in Figure 2.2 (b). The technology depends on coating the paper with microscopic capsules of another material, such as polyethylene. This layer can expand bidirectionally, meaning upward or downward, when heat is applied to it, creating a similar effect to the embossed paper. Depending on the coating material, the color, structure and strength of the tactile format changes. The production process of tactile information using swell paper consists of first printing the data on the paper using normal printer then passing it in a heating machine of around 120–125 °C, the marked areas expand as they are absorb the heat more than the white areas. The resolution of the capsules are around 127 capsules/in which means that it does not even require a specific printer as a normal laser printer with 300 dots/in can be used or even using the pen for drawing [26]. Another advantage of the swell paper tactile graphics is the possibility to produce different heights which can be used to provide more information aspects. However, the heating system is not cheap and creating the master or the original shaper requires a lot of time and skill.

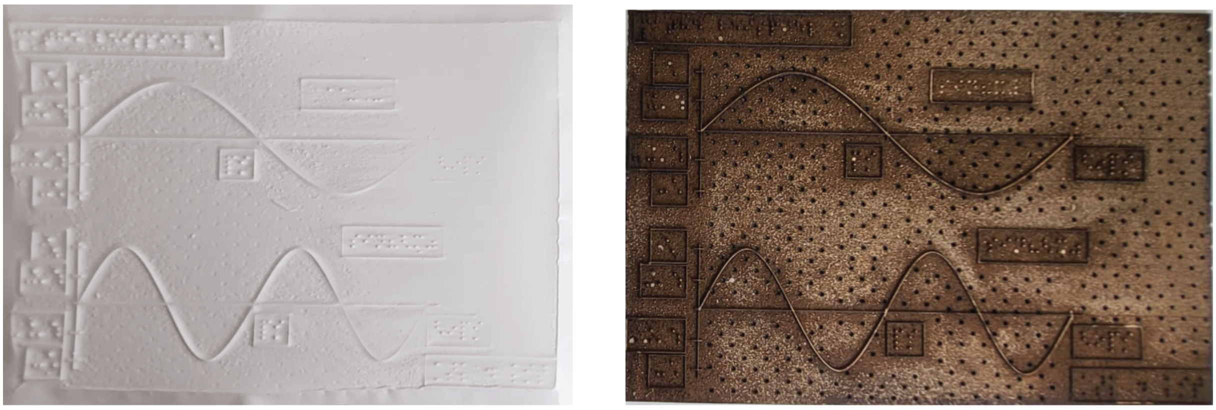


(a) (b)

Figure 2.2: Figure: Tactile documents using (a) embossed paper and (b) swell paper for Braille and graphics.

Another physical method that is used to produce tactile graphics is vacuum forming with thermoplastic sheets. This technique involves heating a thin plastic film, shown in Figure 2.3 (a), until it becomes pliable, then shaping it over a mold that represents the desired tactile form, shown in Figure 2.3 (b). The mold which is typically made from a durable material such as wood, clay, or a 3D-printed object contains the raised outlines or contours of the graphic to be reproduced. Once the heated sheet is placed over the mold, a vacuum is applied underneath, causing the softened plastic to conform tightly to the mold's surface. As the plastic cools, it hardens into a durable tactile sheet that preserves the raised form of the original mold. This method allows for the production of relatively detailed and sturdy tactile representations, suitable for repeated use in educational or orientation contexts [26].

Other approaches involve the use of physical materials to create tactile representations, often relying on fabrication techniques such as laser cutting or 3D printing. Laser cutting is commonly used with materials like plastic, wood,



(a) (b)

Figure 2.3: Figure: (a) Vacuum-formed tactile graphic; (b) laser-cut master used for forming.

or plywood to engrave or cut precise tactile designs into flat surface, as shown in Figure 2.4 (a). This method is particularly effective for producing tactile maps, labeled diagrams, allowing for high spatial accuracy and readability. In contrast, 3D printing enables the construction of 3D tactile models and is frequently used in educational and navigational contexts [27] to convey visual information such as architectural structures, or scientific illustrations, as shown in Figure 2.4 (b). Both methods allow for the creation of customized and durable tactile materials. However, they are better suited for static content, as producing and updating these materials can be time-consuming and less scalable when dealing with frequently changing information or diverse user needs.

(a) (b)

Figure 2.4: Figure: (a) Laser engraved wooden representation of the structure of a fly; (b) 3D printed illustration of an insect.

In comparison to the previously mentioned methods that rely on specialized equipment such as embossers or swell paper printers, which may be costly or unavailable to many individuals, there are more accessible and affordable alternatives for creating tactile representations. One commonly used tool is the raised line drawing board, which consists of a special plastic sheet that produces an immediate raised line wherever a stylus is applied [28]. This enables users to create tactile diagrams or sketches in real time, without requiring any digital processing. Similar low-cost approaches involve the use of everyday or repurposed materials. For example, flannel boards allow for arranging tactile shapes cut from felt or similar fabrics to represent different components of a diagram or interface [29, 30]. Additionally, magnetic boards combined with movable magnetic shapes offer a reusable and interactive platform for constructing tactile layouts or diagrams. These methods are often favored in educational settings or in participatory design workshops with blind users due to their simplicity, flexibility, and low material cost [31].

In literature, there has been extensive work on how physical methods can be used to represent complex diagrams, such as the ones used in STEM fields. An example of this is the work of Doherty et al. [32] which presented a method to make software modeling languages, such as UML diagrams, accessible to computer science students who are BLV using 3D-printed materials. The first step in their work was to automate the process of converting UML diagrams into a format that can be printed using a 3D printer. For this purpose, they created a software that parses UML diagrams in XML format, created by the online tool *visual paradigm* [33], and utilized *openSCAD* library [34] to create 3D CAD models from the diagram. The tool extracts both geometrical information and any existing text in the diagrams. After the extraction, the created 3D models containing the text information are passed to a stereolithography 3D printer *MakerBot* [35], to print the final haptic representation.

The researches noted few disadvantages to this approach. The first issue was related to the extensibility of the approach as the XML format generated from visual paradigm can not be used by other software programs, which shows the need for a common language or variation of XML. Another issue was related to the difficulty of including Braille text, as Braille characters require significantly more space than is typically available within the 3D printing area. Additionally, maintaining consistency in how connector endpoint positions are represented and determining appropriate diagram scaling presented further challenges. Finally, the researchers noted that this method required 1.5 to 2 hours to create UML diagrams of 10 to 15 elements. Evaluations of this method were conducted by the researchers to assess the usability of this method when conducted by users who are BLV.

In a similar approach by Brookshire et al. [36], the researcher aimed to allow visual impaired students to work with their sighted colleges to create UML diagrams of a database. The students were instructed to create class diagrams, where the sighted student used Visio software [37], while the visually impaired student used physical materials such as cardboard, paper, pushpins and plastic 6 mm thin strips. In the first trial, problems rose related to the thickness of the cardboard used, however, in later trials the method was successful to allow the visually impaired student to create a similar diagram to his sighted college. The student found the approach superior to audio-based methods for accessing diagrams, due to the fact that this approach allowed him to have an overview of the diagram.

Owen et al. [30] presented a similar method that represents the elements and relations in UML diagrams on a corkboard using Post-it notes, rubber bands, and push pins. This method was mainly used for teaching class and state diagrams. While these methods offer several advantages over textual approaches for teaching UML diagrams, such as providing a more visual and interactive learning experience, creating physical representations of UML diagrams can be time-consuming and may not be feasible where individuals who are BLV may not have access to the necessary materials.

2.5 Audio-Based Representation Methods

In addition to the physical representations to make information accessible, there exist solutions that are mainly based on the auditory modality. These solutions can be further categorized to sonfication-based methods and speech synthesis based methods. Sonification means conveying information using non-speech sounds [38]. Sonification is often used with visualization context in making graphical information such as charts, diagrams, maps or GUIs accessible through audio [39, 40, 41]. Speech synthesis on the other hand is often used for textual information. With an exception that some research efforts have explored how different sonification and speech synthesis solutions can be used for different applications. In this section, some of the efforts in the literature related to making information accessible using auditory modalities are presented.

2.5.1 Sonification Methods

Alty et al. [40] introduced a tool called *AUDIOGRAPH* which aims to provide access to graphical information on the computer using audio only presenting a complete auditory interface for users who are BLV. Their approach provides BLV users with three types of information: information related to the graphical elements, such as the type, size , shape and the position of the elements. The second information is related to the position of the cursor. Third information related to the overall position of the objects existing on the screen. The first information is provided by the tool by mapping the graphical shape and position of the elements using music. For example, by mapping the distances on one axis to the pitch, while differentiating the axis-es by timbre (piano and organ). For example, two elements sharing the same y coordinates but different x-coordinate would have the same timbre but different pitches. The information regarding the overall position of the objects is provided by using different scanning mechanisms, top-down, center and ascending. For example in the top-down, the music is provided to the user corresponding to the element from top to down. This approach was shown that users were able to know the number and distributions of the elements, while failed to have a feeling for the size of the elements.

In a similar approach by Morris et al. [41], the researchers introduced *soundgraphs*, which are a translation of 2D line graphs into audio images. The method utilizes line graph plots in form of mathematical function or as (x,y) pairs of points in table representation to create around three seconds playback of audio. Their approach works as follows, the data points are mapped to a range of 0 to 3, while the y-values are scaled and mapped to the range of pitches obtained by the system hardware used. Finally, an output sine wave is generated with 1000 sample points.

The soundgraphs also include additional audio cues to convey other aspects of the mathematical function, such as global maxima and minima and adding overtones to represent the first derivatives and indicate the rate of changes. The researches conduced few experiments with seven blind and seven blindfolded participants to test the system and compare it to tactile representation. The results indicated that using audio could be faster (19.3 minutes) in comparison to 26.2 minutes using the tactile, whereas the overall accuracy for the tactile materials was 88.3% in comparison to 83.4% using the sounds graphs.

In the context of mathematical functions, Grond et al. [42] explored how to represent them interactively through sonification for teaching purposes. Their *SonicFunction* system combines discrete and continuous forms of acoustic representation. Continuous sonification conveys the smooth behavior of functions, while discrete sonification supports stepwise navigation along the x-axis. Additionally, derivatives of the function were mapped to changes in amplitude, allowing users to perceive variations in slope. A study with 14 visually impaired students demonstrated that such auditory interfaces can support meaningful interpretation of graphs, particularly when including derivative and sign information. This work highlights the potential of multimodal representations, specifically auditory feedback, for non-visual access to STEM content.

Stockman et al. [43] explored how sonification can be utilized for improving the accessibility of spreadsheets. By designing a prototype that allows users to interactively explore spreadsheet data through non-speech audio cues, the authors showed that sonification can support tasks such as identifying cell values, understanding patterns, and navigating data structures. The researchers showed that sonification can provide more intuitive overview of data that what can be obtained using speech-based methods.

In the context of visual information in the form of maps, Heuten et al. [44] analyzed the use of sonification for making maps accessible to users who are BLV using 3D sonification. 3D in this case means the use of 3D virtual sound room, such that sounds are played in a virtual room by maintaining a relative position equivalent to the original position of the object on the map. By employing different sounds and volumes, the researchers could convey the different distances to the objects on the map. However this approach was tested with only sighted users, therefore further tests would be necessary to confirm the befit of using 3D sonfication in the case of users who are BLV.

2.5.2 Speech-Based Methods

Synthesized speech remains one of the most widely used formats for accessing information among individuals who are BLV who use computers or mobile devices [45]. With sufficient hearing ability, users can listen to text content through auditory feedback instead of relying on tactile perception. This is typically facilitated by screen readers which are software tools that convert digital text into synthesized speech, allowing users to navigate and interact with digital interfaces non-visually.

Screen readers such as *JAWS* [46], *NVDA* [47], and *VoiceOver* [48] enable users to listen to the content displayed on screen. They offer granular control over how information is presented, including the ability to adjust reading speed and navigate content character by character, word by word, or even line by line. This level of control supports flexible reading strategies and can accommodate a variety of user preferences and contexts. Importantly, screen readers provide access for those who can not read Braille, offering an alternative means to engage with digital content independently. Screen redears can achieve very high rates reaching up to 500 words/min [49].

In regard of digital documents, many researchers have explored how complex document structures can be made more accessible through linear, 1D representations that work well with screen readers. One approach involved converting documents into HTML formats that preserve semantic structure while flattening spatial layout. For instance, Wang et al. [50] developed a method for making scientific documents more accessible by extracting the reading order of different elements and organizing them into a hierarchical HTML structure. Similarly, Peng et al. [51] proposed a system for enhancing slide deck accessibility by creating a nested hierarchy of content, allowing users to navigate from general slide descriptions to more specific details. While effective for text navigation, these 1D representations sacrifice the spatial relationships and layout information that are often crucial for understanding documents.

Some previous work explored ways to improve screen readers by enhancing their interactive feature. For instance, Khurana et al. [52] introduced a system that utilizes various keyboard surface interactions to represent visual-spatial elements such as page menus, lists, and maps. Similarly, Gadde et al. [53] presented *DASX* which is a system that allows users to quickly navigate to the most relevant section within a page using a single shortcut. Another innovative approach, proposed by Vtyurina et al. [54], integrated smartwatch/smartphone applications with screen readers. This approach incorporated hand gestures, and voice commands to navigate within the document, enhancing the reading experience for blind individuals.

Ahmed et al. [55] introduced another method to allow blind users to skim through documents without relying on visual cues. In their approach, users are presented with keywords collected from the page text, organized based on topic similarity. Subsequently, a summary is generated from these keywords. Their research findings suggest that this technique can be valuable for providing screen reader users with a high-level overview of a page.

While screen readers are effective for structured text and interface navigation, they are less suited to conveying spatial layout, visual hierarchy, or visual content such as diagrams, tables, and images. In these cases, users often rely on textual descriptions, which may lack sufficient detail or be entirely unavailable, limiting access to key aspects of the content. Additionally, in the case of graphical information, the presence of good alternative texts to describe the graphic is essential. Therefore that have been many efforts in the literature for how alternative texts should be created and how to create them. Methods for creating alternative text in the literature can be categorized into: manual generation by sighted users [56], or automatic methods using computer algorithms or computer-vision methods, or finally hybrid methods which combine both of the last approaches.

Choi et al. [57] presented an approach for converting charts into a table format that includes information about the chart type, shapes and labels which can be then accessed by screen readers. In their approach they proposed a pipeline for automatic the process of converting bar charts, pie charts and line charts in raster format into an accessible table format. By using Convolutional Neural Networks (CNNs) the researchers to classify the charts. Afterwards, text such as labels, titles, legends are extracted using textual region detection models and text recognition using Optical Character Recognition (OCR). Finally, the different charts are decoded to extract the data. This approach was evaluated by only three blind users, who mentioned several usability problems with the approach. This included, the problem with table captions when they are too long, as they were reported by the users to be slowing their navigation. This was then adjusted by the researchers and included before the table. Moreover, using long floating point numbers was reported to be hard to remember which was also changed later to an integer representation. Additionally, robustness was one of the open question mentioned by one of the participants. Also in this approach few limitations are noted, such as bar charts are only allowed in vertical from and the legends should always have distinct colors.

Brewster [58] also conducted an experiment where both speech-based and sonification methods were used to improve accessibility of graphs for users who are BLV. By employing sounds created by Musical Instrument Digital Interface (MIDI) synthesizer, he mapped the y-axis values to the note numbers between 0 and 127. The speech-based part was employed for allowing the users to choose to either listen to the different values in a spoken manner or using the combination. The researcher conducted the experiments with 16 participants with diverse visual impairment. The results showed that the use of speech-based and sonification is an approach worth analyzing, as it can improve the usability and the workload associated with accessing visualizations.

In general, accessibility solutions for digital information that depend only on the audio modality is not always practical, since some users can have hearing problems and even for users who do not have such issues, noisy environments can be challenging. For example, previous research showed that social events such as conferences, classrooms, libraries can be challenging for screen reader users [59]. Some of the options to mitigate this problem would be to increase the volume to overcome the noise, however, this can still pose a problem as the users would need to quickly react to sudden noise by adjusting the volume which can distract the users. Additionally, in mobility applications, unceasing the volume to much would remove the surrounding sound cues around the user, which can endanger them [60].

2.6 Hybrid Representation Methods

While both tactile and audio-based methods offer distinct advantages for providing access to digital information for individuals who are BLV, recent research has explored combining these modalities to overcome the limitations of using either alone. Hybrid systems aim to integrate the spatial and structural clarity of tactile formats with the descriptive and flexible capabilities of audio feedback. For example, augmenting tactile representations such as raised-line maps or diagrams with speech output can help address the challenge of representing complex textual information, such as Braille labels or detailed explanations, in limited tactile space. As discussed in Section 2.4, this is particularly relevant in contexts where space constraints or content density make Braille impractical.

Several approaches in the literature have proposed hybrid systems that synchronize touch input on tactile surfaces with audio cues. These systems often allow users to explore tactile graphics and receive audio descriptions of specific regions or elements when touched, thereby enhancing understanding while preserving spatial layout. Some systems use touch-sensitive overlays or sensors to detect user interaction, while others pair physical tactile materials with external devices such as smartphones or computers that provide the audio output.

The following sections present examples from the literature of hybrid methods including vibro-tactile and audio combinations, static hybrid approaches that do not allow interaction with the content, and dynamic methods that support interactive exploration.

2.6.1 Vibro-Audio and Vibro-Tactile Methods

Some hybrid methods depend on combining vibrations with audio feedback or tactile formats. For example, Goncu et al. [21] introduced *GraVVITAS* (Graphics Viewer using Vibration, Interactive Touch, Audio, and Speech), a system designed to make graphical content in SVG format accessible. The system combines a touch-sensitive tablet with vibrating motors attached to the fingers to provide multimodal feedback. The tablet detects finger positions, while audio output supports navigation, provides an overview of the graphic, and delivers textual information upon user queries.

Testing the usability of the approach with participants who are BLV revealed challenges in distinguishing whether a finger was touching a graphical element. To address this, the system incorporated gloves fitted with four vibrating actuators, one for each finger, since the display could only track up to four fingers simultaneously. The vibration intensity varied depending on the color of the graphical element being touched.

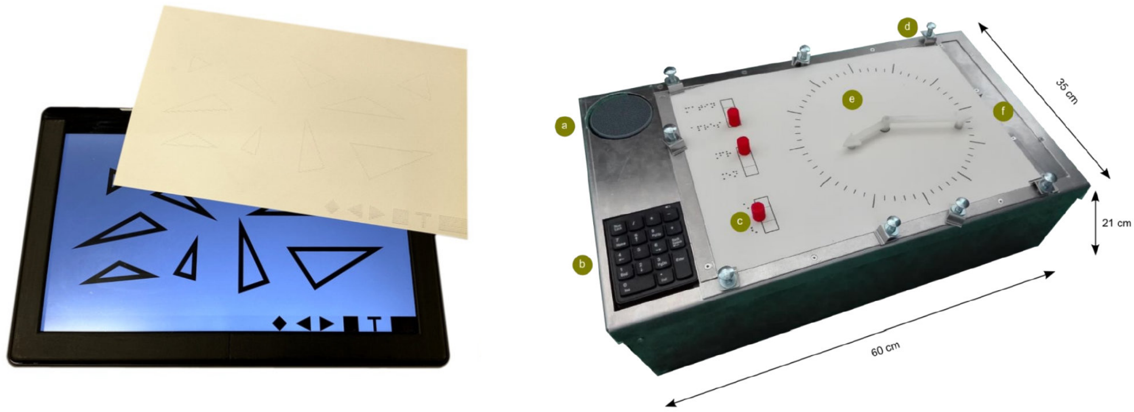
Despite these improvements, several usability challenges were noted. Identifying which finger was in contact with the display proved difficult, and users had to be trained to flatten their fingers appropriately to maintain consistent contact. Textual elements also presented difficulties, as their spatial requirements made them harder to represent effectively. Furthermore, the system required an additional step of manually embedding metadata in the SVG files to describe each element for accessibility purposes.

In a similar approach, Giudice et al. [22] introduced a vibro-audio interface that employed distinct vibration patterns to differentiate between edges and vertices on a touch-sensitive tablet. By utilizing the tablet's embedded motor, the system represented vertices through pulsing vibrations, while edges were indicated using continuous vibrations. Audio feedback, delivered through speech output, provided users with additional information about the graphical content, such as announcing the name of each bar in a bar chart when tapped. The primary aim of this interface was to offer users a spatial representation of graphical information using a combination of tactile and audio cues. However, user testing revealed that BLV participants experienced difficulty tracing curved lines and moving laterally across the tablet's surface, particularly in comparison to using textured physical materials such as embossed paper. These findings highlighted the need for additional orientation cues when exploring graphical information on smooth, untextured touchscreens, such as tablets or smartphones.

Another approach by Safi et al. [23] to preserve document layouts, while still using screen readers, employed vibration sensors to represent the document layout. In this research, they developed a finger-sized embedded system with a micro-vibrator. The intensity and the frequency of the vibration are adjusted based on the structure of the touched document on the tablet. Similarly, Maurel et al. [24] proposed a strategy for allowing blind users to access vibro-tactile documents using hand-mounted actuators that deliver localized vibrations with varying intensities and frequencies. By correlating light intensity with vibration frequency, users could distinguish between different elements and borders within the layout. While their research focused on webpage layouts, evaluation with blind users was not conducted to assess the benefits of such approaches.

2.6.2 Static Audio-Tactile Methods

Raynal et al. [62] presented the development of *FlexiBoard*, which is a system designed to enhance access to graphical information in tactile materials by introducing interactive features. The system consists of a wooden frame housing a camera and a Raspberry Pi for object tracking, enabling the detection of the position of tangible elements placed on the board, as shown in Figure 2.5 (b). By placing magnets beneath the top surface of the board, the system tracks the movement of tangible objects, each comprising two magnetically connected parts (top and bottom) created using a 3D printer. These magnets allow the physical objects to remain attached to the surface while enabling interaction. Audio feedback is used to read text labels, provide navigation instructions, and offer menu options. The first use case of this system focused on navigation scenarios, where users were asked to locate



(a) (b)

Figure 2.5: Hybrid methods for representing information for users who are BLV: (a) tactile document representation hybrid method by Mackowski et al. [61], (b) FlexiBoard by Raynal et al. [62]

specific places on a map. The system was also tested in the context of board games to explore additional interaction possibilities.

The system presented some limitations, for example, users encountered difficulties when moving the tangible objects, as they did not always glide smoothly across the surface. The design required the bottom part of the object to remain aligned and attached to the top part; if the pieces became detached, reattaching them was not straightforward for users. Additionally, challenges related to the tracking algorithm and localization accuracy were observed during testing.

In an approach by Li et al. [25], which highlights the hybrid use of audio and tactile methods, the researchers explored how embossed papers can be used in combination with tablets to provide ways to access layouts structures used in web-pages. Therefore, they presented a tool to automatically extract the structure of web-pages and utilized screen readers to speak out the content, as well as the meta-content represented in the heading level. Their tool creates embossed paper templates of web pages that can be laid on a tablet and be used to listen to the page content and layout as well as to edit it. This approach was however only implemented for web pages and was evaluated with a small sample number of two blind users. Also the researchers highlights the difficulty due to the time it takes to fabricate and replace the tactile sheets which does not allow for an interactive workflow, suggesting that using refreshable tactile displays would solve this issue.

Other similar approaches utilized embossed papers in combination with audio feedback is the work of Chase et al. [63], which introduced a system to allow blind users to explore tactile graphics using skin-stretch mechanism accompanied with audio feedback. By using a wrist-worn device that provides feedback to the back of hand while exploring a tactile graphic positioned on a touch screen. Mackowski et al. [61] also introduced an approach for representing documents. In this approach, variant heights and textures are assigned to document elements. A significant advantage of these printed tactile materials is that they are affordable; however, they only convey static layouts. Once printed, they cannot be altered and provide no interactions.

2.6.3 Dynamic Audio-Tactile Methods

In comparison to static audio-tactile methods presented in the previous section, where the information is presented to the user in a static manner where no change in the presented information can happen upon interacting with it. There exist other dynamic methods which enable the users to interact with the information presented and the information change according to the interaction. This is achieved using 2D refreshable tactile displays. Tactile displays are a point-based displays that allow dynamic representation of content such as Braille text or 2D visual information, depending on the available area. Such devices are available in varying number of actuators. The actuators are the single pins that exist on the display or can be considered as the pixels of the screen. In comparison to the digital screens, the pixels or what is also called as tactile pixels or *taxels* can only have two different states or values which are high or low since they can either be raised or lowered. In other advanced type of these displays this can be more than two values if the pins can have different heights.

Some of the important specifications of 2D refreshable tactile displays are : (a) **size** of the display: which defines how large the display is and the total number of the taxels, (b) **resolution**: which is how closely the taxels are placed and is often defines in mm, (c) **refresh rate**: which defines how fast the pins can be raised or lowered or how much time it required to refresh the whole area of taxels. The refresh rate depends on the actuation mechanism used which defines how the vertical movement of the pins is achieved. Scientific literature includes many approaches for the actuation that use different technologies such as electromechanical [64, 65], shape memory alloys [66, 67], pneumatic [68], and piezoelectric [69].

2D refreshable tactile displays based on electromechanical concepts, use servo motors for example to control the motion of the pins. The work of Wagner et al. [65] showed how a 6*6 2D tactile display can be created using RC servomotors. The display was created with 2 mm spacing and 1 mm pin diameter. Similarly, Leonardis et al. [64] presented an approach that depends on the use of electromagnetic field by utilizing a single moving electromagnetic coil that is used to move or align the ferromagnetic pins. This refreshing configuration is used to raise the individual pins and move them to a leveraged position in order to achieve the high position. The refresh rate that was obtained used this method was 14 seconds. However the price for producing such tactile Braille displays was quite high and could reach around 8000 euros for 80 cells.

Some actuation concepts depend on the use of materials that have the ability to deform to recover and obtain the original shaper after removing the stimuli source, example of this is shape memory alloys (SMA) and shape memory polymers (SMP). The work of Besse et al. [66] showed a design of a SMP refreshable tactile display with 4*4 taxels. The prototype required 5 seconds to refresh the 16 taxels. Tactile Braille displays that use SMA materials have the advantage of lower cost and lightweight which makes it possible to create portable tactile Braille displays. The work of Velazquez et al. [67] shows a prototype that was creating with 64 taxels and only 200 grams. The actuators were created using spring which when heated gets contracted, lowering the pin and when disconnecting the electrical current the temperature decreased and therefore expands pushing the pin up.

Pneumatic tactile displays use air pressure to control the movement of pins on a flexible surface. Each pin has an air-driven mechanism that can move up and down, allowing users to feel different tactile patterns. Previous examples of these kinds of displays in the literature are the work of Gutierrez et al. [68] which showed a prototype of 5*5 tactile display, with 2.5 mm distance between the taxels.

2D refreshable tactile displays thar use piezoelectric actuators are very common, due to the ability to obtain high reliability, high refresh rates and also with low power consumption [64]. Piezoelectric tactile displays use piezoelectric actuators to create small vibrations or movements in a pin matrix. These displays are generally used for creating vibrations or subtle tactile sensations that can be felt by users. The working principle of the actuation is that Piezoelectric materials change shape when an electric voltage is applied, Many of the current available devices use this concept for actuation, such as BrailleDis 9000 [70], HyperBraille display [69]. However, piezoelectric actuators require one actuator per pin which make the device big and also cost a lot. The following section introduces some of the currently commercially available 2D refreshable tactile displays.

Figure 2.6: Commercially available 2D tactile displays: (a) Hyperbraille, (b) Hyperflat, (c) Tactile2D , (d) Graphiti, (e) Graphiti plus, (f) Dotpad, (g) Tactonom pro, (h) Monarch

2.6.3.1 Existing 2D Tactile Braille Displays

Given the benefits of 2D tactile Braille displays in enhancing the performance of individual who are BLV performance in spatial problem-solving tasks compared to traditional raised-line paper methods [71], there has been an increasing attention in research and industry on the development of multi-line tactile displays, the availability and performance of such technologies are expected to improve in the future, however, there are currently several commercially developed devices that are build using the aforementioned actuation technologies. These displays vary in form and function, from devices that only aim to provide users with access to textual information and other generic devices that provide interactive platforms for exploring both textual and visual information. This section presents a selection of notable devices along with their specifications. The overview focuses on currently available 2D tactile displays and their key characteristics including display size, resolution, and refresh rates. Moreover, the software capabilities of the available devices for presenting digital textual and graphical information used in STEM fields are presented.

Metec Ag Displays. Several 2D tactile display devices are available from the company Metec Ag. [69]. These include the *HyperBraille*, *Hyperflat*, and *Tactile 2D*, as shown in Figure 2.6 (a, b, and c, respectively). The HyperBraille display is a stationary device, while the Hyperflat and Tactile 2D are portable. The devices are capable of handling touch interactions, and the actuation technology used is based on piezoelectric actuators. All three models support high refresh rates of up to 20 Hz. A summary of the technical specifications of each device are shown in Table 2.1. All three devices support the proprietary *MVBD* software, which runs on Windows OS and allows users to access computer screen content via the tactile display. This software also includes OCR capabilities to extract text from documents. In addition, the Hyperflat supports a specialized software application called *HyperBrailleGeo*, which enables users to interact with mathematical graphs created in GeoGebra.

Device	**Area W*H in mm, Pins**	**Refresh rate**	**Mobile**	**SW Capabilities**	**Touch**	**Actuation**
HyperBraille	150×260 (6240)	20Hz	No	MVBD	5-point	Piezoelectric
Hyperflatt	190×120 (3648)	20Hz	Yes	MVBD, HyperBrailleGro	10-point	Piezoelectric
Tactile2D	120×97 (1872)	20Hz	Yes	MVBD	10-point	Piezoelectric

Table 2.1: Comparison of HyperBraille, Hyperflat, and Tactile2D

Orbit Research has developed two 2D tactile Braille displays: the *Graphiti* and the *Graphiti Plus*, shown in Figure 2.6 (d) and (e) respectively. The *Graphiti* features a 60×40 pin array, while the *Graphiti Plus* offers a higher pin count (3648 pins), includes a 40-cell single-line Braille display, and supports multi-level actuation. Both devices incorporate multi-point touch capabilities and utilize Orbit's proprietary *Tactuator* technology for actuation. In terms of software functionality, both displays are primarily intended to be used as external tactile monitors connected to a computer or smartphone to render digital content. A number of built-in applications are also included, such as a clock, alarm, calendar, and calculator. Furthermore, an Application Programmable Interface (API) is provided for developers, enabling programmatic control of individual pins.

The display area of both devices is approximately 295×269 mm, and they offer a refresh rate of about 0.2 Hz. This makes them particularly well suited for static or slowly changing tactile content. Despite their relatively large display size, the devices are portable and support rich interaction through direct touch input.

Dot Incorporation developed the *DotPad*, shown in Figure 2.6 (f), which is one of the modern 2D tactile Braille displays currently available. It is a portable device with a 30×10 pin array that uses electromagnetic actuators. The device measures 273.6(L) × 228.5(W) mm and weighs approximately 1.2 kg. It includes Bluetooth and WiFi connectivity and has a refresh rate of around 5 seconds per screen. Regarding its software capabilities, the device cannot be considered a standalone unit, but rather a secondary tactile display. By connecting it to an iOS device (tablet or phone), users can access two applications provided by the company and display them in tactile format on the device.

The software includes *Dot Canvas*, which allows drawing and supports loading images and PDF documents. However, in testing, only simple images were rendered effectively, and text elements were displayed without structural interpretation. For PDFs, only the plain text is extracted using OCR, while images, layout order, and certain text elements are ignored. Another available iOS application is *Dot Book*, a basic text editor. Additionally, for developers, an emulator called *Dot Emulator* is provided on iOS devices, enabling testing of software without requiring the physical hardware. An SDK is available to support content development.

Inventivio developed the *Tactonom Pro*, which is a 2D tactile display designed to represent digital information in two dimensions, as shown in Figure 2.6 (g). It features an array of around 10,000 (89 * 119) pins actuated by electromagnets, using metal spheres positioned between two conductive layers. The refresh rate is approximately 15 seconds per image. The device includes a camera to detect finger position, emulating touch functionality. As the device is not yet commercially available, its full software capabilities remain unclear. However, according to the manufacturer's website, it is expected to support interaction with digital documents, graphs, mathematical formulas, and websites. A dedicated software application for displaying Excel spreadsheets is also mentioned [72]. However, due to its size and weight, the *Tactonom Pro* is not designed to be a portable device, rather stationary.

American Printing House developed *Monarch* which is another 2D tactile Braille display, shown in Figure 2.6 (h). The device features 480 Braille cells and measures 403.55 mm (W) × 266.5 mm (L), weighing approximately 2.1 kg. It employs the same electromagnetic actuation technology as the DotPad, resulting in a similar refresh rate of around 5 seconds per screen. Designed to be portable, the Monarch includes internal storage and supports several built-in software applications, such as a Braille editor, calculator, graphic viewer, and file manager. The device uses an infrared sensor to detect finger position and emulate touch interaction. However, the device is not yet commercially available.

2.7 Designing Tactile User Interfaces for 2D Refreshable Tactile Displays

The software ecosystems currently associated with 2D tactile displays are not sufficiently mature to support effective access to complex STEM content, as demonstrated by the analysis of existing refreshable tactile displays, shown in Section 2.6.3.1. Many of the current devices lack comprehensive software solutions and remain unavailable on the commercial market, contributing to a scarcity of detailed information regarding the design methodologies and UI frameworks employed. Although most of the aforementioned producers offer an API to encourage developers to create software for their devices, there is a pronounced deficiency in established guidelines or standards for developing software specifically tailored to these devices. This situation underscores the necessity for a systematic investigation into the design of tactile user interfaces, which the following sections address through an analysis of existing TUIs in the literature, as well as a review of available design principles for tactile interactions on such devices.

2.7.1 Existing Examples of Tactile User Interfaces

A User Interface (UI), as defined by Galitz [73], is a subfield of Human Computer Interaction (HCI) concerned with the point of interaction between a user and a machine. UIs can take various forms, including physical components such as keyboards and mice, or software-based interfaces found in websites, mobile applications, and embedded systems. Within this domain, GUIs represent a subset that conveys digital information visually through elements such as buttons, menus, and windows, allowing users to interact with content graphically. Well-designed GUIs can reduce cognitive load and facilitate faster information processing for sighted users ([73]).

In the context of 2D tactile displays, the representation of digital information over a two-dimensional area shares some conceptual similarities with GUIs but differs fundamentally in modality. Instead of using visual graphics, content is rendered in a tactile format. As a result, the design and interaction mechanisms for tactile displays diverge significantly from those used in graphical environments. While visual cues such as color, icons, or animation are unavailable, tactile interfaces rely on tactile patterns, layouts, and audio feedback to communicate information.

Designing effective UIs for tactile displays must address both *accessibility* and *usability* aspects. Accessibility ensures that users who are BLV can perceive and interact with content, while usability ensures that the interaction is efficient, goal-oriented, and satisfying. There are limited resources in the literature on how user interfaces can be designed for 2D refreshable tactile displays. In this section, an overview of the existing approaches are presented.

In the context of web browsing, Rotard et al. [74] proposed a TUI that allows users who are BLV to access web pages using a 2D tactile display. Their system used the Metec display with a resolution of 120×60 taxels. To minimize cognitive load, their transformation pipeline for processing HTML and XHTML documents restructured layouts to avoid horizontal scrolling. For scaling the images, they adopted a square root function instead of a linear scaling function. This choice was motivated by their observation that linear scaling excessively reduced the size of small images, which are often crucial for navigation and interface comprehension. The square root function reduced this issue by shrinking small images less aggressively. The system also provided options for users to manually scale images up or down. Tables were simplified by reducing border thickness to a single taxel, and margins and spacing were optimized to conserve space. List elements were rendered on separate lines in Braille, with bullet points or numbers represented as an 8-dot Braille cell with all dots raised. Additionally, style information was embedded into the text representation.

The TUI supported limited interaction techniques. Only hypertext links could be selected using a dedicated key. Users could cycle through links, and the currently highlighted element would blink to indicate selection. Upon activation, if the link pointed to an image, the system entered an image exploration mode; if it linked to another document, it would be displayed using the same layout transformation techniques. In image exploration mode, users could apply filters and zoom in or out. For bitmap images, the system used histogram-based thresholding to distinguish foreground from background. The threshold value was initially computed based on the most frequent value in the histogram but could also be adjusted by the user. For SVG images, several filters were implemented, such as removing color fills and gradients. A text filter was also available to enable users to navigate between text elements sequentially, with blinking used for highlighting. However, text in SVGs was not rendered in Braille, as it would have required excessive space on the tactile display. The TUI was implemented in *Java* and employed *FreeTTS* for audio output. In preliminary tests, users found the interface useful and preferred the SVG format over bitmap images, describing it as more flexible. In particular, the ability to remove color fillings was appreciated, as it helped users better understand object boundaries and overall semantic structure. However, no formal evaluation of the system was conducted.

Loitsch et al. [75] presented a design of a TUI for rendering UML sequence diagrams on the HyperBraille display [69] with 120×60 taxels. Their TUI included scroll bars on the sides of the display to indicate the user's current position, supporting both horizontal and vertical scrolling. To save space, text elements were replaced with plus signs, which users could press to hear the corresponding text via audio feedback. Interaction techniques involved touch gestures for panning and scrolling, as well as activating the plus signs for text reading.

The evaluation of this tactile user interface with seven participants who are blind revealed that all users desired more overview functionality. Specifically, excessive panning and scrolling were found to be counterproductive, leading to difficulties in maintaining orientation. Additionally, participants requested auditory information about the total number of objects in the diagram upon opening it, to better understand the content at a glance. The study concluded that the small resolution of the tactile display causes orientation challenges that require novel interaction concepts to address. Furthermore, the need for editing capabilities within such interfaces was emphasized to enhance usability and user control.

Another TUI was proposed by Perscher et al. [76], who explored how 2D tactile Braille displays can be used to present multiple windows simultaneously, each displaying different types of information. Their system was also developed to run on the HyperBraille display [69] with 120×60 taxels and was designed through an iterative, user-centered process involving embossed paper prototypes tested in collaboration with blind users.

In their design, the display area was divided into the following six distinct regions:

1. **Header Region:** displayed the title of the currently active window.
2. **View Type Region:** indicated the active view mode (text, outline, symbol, or layout).
3. **Structure Region:** provided an overview of the horizontal structure of the open window.
4. **Detail Region:** conveyed contextual information about the focused element or displayed temporary system messages (e.g., operation feedback).
5. **Window Title Region:** showed the titles of all open windows, limited to the first four letters of each.
6. **Body Region:** displayed the main window content, allowed two windows to be shown simultaneously, and included a vertical scroll-bar for navigation.

Interaction was supported through built-in device buttons, an external keyboard, and touch gestures. To distinguish between gestures and exploratory touch, gesture input was only recognized when a specific key was held. Supported interactions included resizing windows by performing gestures from the border to the center (or vice versa), and minimizing, maximizing, restoring, or closing windows using buttons. Users could activate windows by single or double tapping. Zooming was implemented through semi-circular (small zoom) or full circular (large zoom) gestures. Panning was supported using three fingers or scroll arrows, while tapping enabled selection or repositioning of elements.

The system was evaluated with eight blind participants. Users found the structure region helpful for locating specific elements and appreciated the detail region for presenting additional contextual information. The ability to zoom, pan, and resize windows was also positively received. However, the need to hold a key during gesture interaction was criticized for lowering usability, and the gesture recognition rate was rated only 2 out of 5, indicating the need for further refinement. Still, participants valued the ability to access an overview of desktop icons, which received an average rating of 4.1 out of 5.

To address disorientation during zooming, previously highlighted by Loitsch et al. [75], the researchers implemented a dual-view system: one provided an overview with a blinking rectangle indicating the currently zoomed-in area, while the second displayed the magnified content. This approach aimed to support users in maintaining spatial orientation while navigating and exploring content in detail.

Other research efforts have explored the use of 2D refreshable tactile Braille displays for reading digital documents. One such example is the work by Melfi et al. [77], who introduced an approach for presenting PDF documents on a 2D tactile display in combination with a dedicated GUI on a computer. Their interface was developed for the HyperBraille display [69] and supported PDF files. The presentation method relied on rendering document images and representing text as a blinking horizontal line intersected by a small vertical line at its center. This blinking mechanism was designed to help users distinguish between textual and graphical elements.

The researchers implemented several interaction techniques such as touch gestures to allow users to select text elements either by double tapping. Additionally, interactions based using combination of touch and buttons to highlight certain element and display the corresponding text on the GUI. A zooming interaction for graphical elements was also included, using a single finger to define the zoom center. Color filtering was enabled via buttons, with each button mapped to a specific color in the graphic, allowing users to toggle individual colors on or off.

However, the interface's ability to handle complex images or scenarios where the number of colors exceeds the number of available buttons remains unclear. The system was evaluated with four blind users, who found the interface to be helpful. Their feedback included a desire for a mobile version with higher resolution and improved graphical representation, particularly for elements like curves.

In navigation context, the work by Ramoa et al. [78] investigated how 2D tactile Braille displays, specifically the Tactonom Pro, can be used to convert maps from PDF format into SVG to present them in an accessible and interactive format for users who are blind or have low vision. A tactile user interface was developed that displays the converted and annotated SVG maps on the device. To facilitate tactile rendering, only geometric elements without a fill property are displayed, and textual content is translated into Braille. The interface supports three levels of interaction: file, map, and system interactions. These include selecting files or on-screen elements by touch in combination with a touch-activation button, and searching for files using a keyboard. Additionally, the system incorporates an audio menu that is navigable using arrow keys on the device. However, the interface was not formally evaluated.

The work of Matsuo et al. [79] presented a tactile user interface that allows blind users to play *Tetris* on the *KGS DotView DV-2* tactile display, which features a 48×32 taxels matrix (1536 taxels), using both tactile and audio feedback. The game supports interaction through either a keyboard or a *Nintendo Joy-Con* joystick. Core interaction concepts include standard game controls such as moving blocks in various directions and rotating them.

Distinct sound effects convey actions like falling, rotating, and moving blocks, as well as indicating when a block becomes fixed. Additionally, speech output is used to announce score updates.

Following an evaluation with six users who are BLV, several improvements were made to enhance interaction and representation. These included allowing users to customize block size, configure button functionality, and adjust the game speed. A blinking tactile area was also added to help predict the falling point of blocks. Users requested more speech-based feedback to provide information about the current and upcoming block shapes, as well as the addition of a tutorial to introduce the different block types and game play mechanics.

2.7.2 Accessible GUI Design Guidelines: Foundations for Tactile User Interfaces

Designing UIs for non-visual platforms such as 2D refreshable tactile Braille displays remains a largely underexplored area. These devices differ fundamentally from visual interfaces in how users perceive, explore, and interact with content. Consequently, there is a pressing need for interface design principles specifically tailored to tactile displays and to the interaction strategies of users who are BLV.

2.7.2.1 GUI Established Design Guidelines

GUI benefit from well-established design principles. A widely recognized Visual Information Seeking Mantra in the field of HCI by Shneiderman [80], presents guidelines for the design of information visualization functionalities. Shneiderman proposes three key elements to enhancing information seeking in a software system as follows:

- **Overview**: users should be presented with a comprehensive overview of the complete dataset prior to delving into specific details. This overview enables users to gain a broad understanding of the overall structures and patterns inherent in the data.
- **Zoom and filter**: users can actively engage with the data by zooming in on points of interest and applying filtering. This allows the users to uncover details and patterns within the selected data points.
- **Details-on-demand**: this element highlights the importance of offering users detailed information only when the users specifically request the information through queries or interactions. This approach promotes user-centered and interactive data visualization.

Similarly, there exist international standard, such as the ISO 9241-110 [81], which defines ergonomic principles for interactive systems, including self-descriptiveness, conformity with user expectations, error tolerance, and individualization.

While these guidelines provide a valuable foundation, they are inherently grounded in visual interaction. Applying them directly to tactile UIs requires careful adaptation to accommodate the unique characteristics of tactile perception, such as sequential exploration, spatial memory, and the integration of non-visual feedback modalities like audio or haptic cues.

2.7.2.2 Design Principles for Accessible Digital Content

This section discusses existing frameworks and guidelines for designing usable and accessible UIs. It begins with an overview of established accessibility principles, introduces key GUI design guidelines, and concludes with a discussion on how these concepts apply to the specific interaction requirements of 2D tactile Braille displays, highlighting the current lack of formalized guidance in this area.

A fundamental aspect of UI design is ensuring that the information presented is accessible. To support this goal, various established guidelines and design principles have been developed to help make digital content inclusive and usable by all individuals, including those with disabilities. One widely recognized framework is the Web Content Accessibility Guidelines (WCAG), developed by the World Wide Web Consortium (W3C). Although originally intended for web content, WCAG is often adapted for other digital formats, such as PDF documents, to support accessibility in broader contexts.

WCAG is built around four foundational principles, summarized by the acronym POUR: Perceivable, Operable, Understandable, and Robust.

1. **Perceivable:** Information and UI components must be presented in ways that users can perceive. For instance, non-textual content such as images, videos, or multimedia should be supplemented with alternatives like text descriptions to make them accessible to users who are BLV.
2. **Operable:** The interface must allow users to interact with it using a variety of input methods. For example, content should be fully accessible via keyboard navigation or alternative input devices.
3. **Understandable:** Users must be able to comprehend both the information presented and the interface itself. Content should be clearly structured, and information should be made available in different formats, languages, or modalities, such as through a screen reader.
4. **Robust:** Content must be compatible with a wide range of current and future user agents, including assistive technologies.

While these principles provide a solid foundation for digital accessibility, their direct application to tactile UIs is still underexplored. Further work is needed to define how concepts like perceivability and operability translate into non-visual interaction paradigms such as those offered by 2D tactile displays.

2.7.2.3 Summary and Insights from Existing TUIs

Beyond GUIs, prior research on TUIs for users who are BLV offers valuable insights into interaction design. These studies have proposed a range of strategies for presenting and navigating digital content through touch, including techniques for structuring information spatially, guiding exploration, and offering contextual feedback. Despite variation in context and content type, several recurring themes and challenges emerge from this body of work. The following points summarize key design patterns and lessons learned from existing TUIs presented in Section 2.7.1 and shown in table 2.2:

1. **Spatial Layout and Overviews:** Most systems attempt to preserve spatial structure by introducing overview modes or multi-region layouts to help users maintain orientation. However, display resolution limits and the cognitive load of panning across content highlight the ongoing need for more efficient navigation strategies.
2. **Interaction Concepts:** Existing TUIs employ a variety of interaction methods, including touch gestures, physical buttons, audio feedback, and sometimes external devices (e.g., keyboards, joysticks). Some systems require combined interactions (e.g., holding a key while gesturing), which may impact usability. Systems offering redundant feedback modalities, such as tactile blinking combined with speech, tend to be preferred.
3. **On-demand rendering of Information:** Text is often rendered selectively or on demand, using strategies like plus signs for expandable content or blinking lines for highlighting. Graphics are processed through techniques such as thresholding, SVG filtering, and color toggling to preserve essential information while minimizing tactile clutter.
4. **Customization Possibilities:** Evaluations with users who are BLV commonly highlight the need for improved overview mechanisms and possibilities to control the amount of information displayed. Additionally,

customizable controls which the user can adjust according to their needs, more detailed audio feedback, and clearer spatial orientation support are also areas for exploration.

Researcher	Context	Display Used	Data Types	Interactions (input)	Representation (output)	Problems / Remarks by Participants
Rotard et al. [74]	Web Browsing	HyperBraille	HTML SVG bitmap	1- Zoom (buttons) 2- Selection (buttons)	1- Filtering for bitmap (thresholding) 2- Filtering for SVG (color fill and gradient) 3- Buildup technique for displaying SVG 4- Vertical scrolling 5- Blinking to highlight selected element	1- Images not clear to the users 2- Transformation schema needs improvement to handle missing HTML tags
Loitsch et al. [75]	Graphs	HyperBraille	Microsoft Visio Formats	1- Pan (touch or buttons)	1- Horizontal and vertical scrolling 2- Text substituted with plus sign 3- Verbal description of diagrams by sighted user	1- Disorientation problems 2- Overview needed 3- Too many scrolling required, leading to high overload 4- Sighted user needed
Perscher et al. [76]	Window System	HyperBraille	GUIs	1- Window operations (buttons) 2- Zoom (touch gesture + button) 3- Pan (touch gesture + button)	1- Four different views for windows (operating, outline, symbol, layout) 2- Divide screen in six regions (header, view type, structure, detail, titles, body) 3- Blinking frame for current position	1- Gestures plus holding a button reported to affect performance
Melfi et al. [77]	Reading	HyperBraille	PDF JPEG	1- Zoom (touch + button) 2- Navigation (buttons) 3- Filter colors (buttons)	1- Text represented by horizontal line with cross at the middle 2- Blinking text elements 3- Filtering existing colors	1- Better representation of graphical information requested 2- Resolution problems
Ramoa et al. [78]	Navigation	Tactonom	SVG	1- Selection (touch + button) 2- Zoom (buttons) 3- Pan (keyboard or arrow buttons) 4- Searching files (keyboard)	1- Only graphical elements with no fill are shown 2- Text displayed in Braille in original size and hidden in zoomed view 3- Files shown as list of Braille text	No evaluation conducted
Matsuo et al. [79]	Gaming	DotView	Own Format	1- Game controls (keyboard and Joy-con Nintendo joystick)	1- Geometrical shapes in tactile format 2- Different sounds for different events (falling block, move, rotate) 3- Supplemental audio for situational changes (score change, game over)	1- Blinking to indicate important positions 2- Customization options (button configuration, block size, speed) 3- Audio info about block shapes

Table 2.2: Summary of Tactile UIs in the literature using 2D tactile displays

Building on established GUI design principles for accessible digital content, along with the insights and lessons learned from existing TUIs, the following chapter presents the design of three TUIs developed as part of this research. Focusing on independent access to content commonly used in STEM fields, the TUIs serve both as functional prototypes and as illustrative examples to inform future design of TUIs for 2D refreshable tactile displays.

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3 Tactile User Interfaces for Accessing Digital Documents and Graphics

This chapter presents three novel TUIs designed to support independent access to common information used in STEM fields, such as documents and graphics for users who are BLV. The TUIs support three common digital content formats: PDF, Electronic Publication (EPUB) [82], and SVG. These interfaces were developed to run on 2D refreshable tactile Braille displays and enable users to explore structured document content and graphical elements through a combination of tactile and audio feedback. The chapter also addresses the technical process involved in document analysis and segmentation of PDF format and vector graphic interpretations. By adapting presentation methods and interaction concepts from the literature and based on the guidelines for creating accessible UIs, discussed in Section 2.7.2.

The chapter addresses the following research questions:

- **RQ1**: How can common digital document formats, such as PDF and EPUB, be analyzed and transformed into formats suitable for tactile exploration on 2D tactile displays?
- **RQ2**: How can TUIs be designed to support independent navigation of different types of document layouts and graphical elements?
- **RQ3**: What interaction concepts are most effective for enabling access to structured document content and vector graphics on 2D tactile Braille displays?

The remainder of this chapter is structured as follows: Section 3.1 discusses the main types of digital document formats and outlines the accessibility challenges associated with EPUB and PDF documents and previous efforts in improving their accessibly for user who are BLV. This section also introduces automated methods for Document Layout Analysis (DLA). Building on this foundation, the chapter then presents the design of the three TUIs for exploring EPUB and PDF documents, and SVG-based vector graphics.

This chapter is based on three publications: Section 3.2 originates from MDPI Multimodal Technologies and Interaction (2024) [2], Section 3.3 from PETRA 2025 [3], and Section 3.4 from the Haptic Symposium 2024 [1]. Portions of the text remain unchanged from the original publications.

3.1 Context

This section presents the common formats for digital documents and discusses some of the efforts for making them accessible to users who are BLV. Additionally, it reviews previous research efforts focused on DLA methods and explores how information and metadata can be extracted from documents using computer-vision methods and machine learning models.

3.1.1 Digital Document Formats: Ebooks

Ebooks are becoming more important with the increasing demand for digital information, as they enable the readers to access books with reduced effort, compared to the traditional paper format [83]. However, for users who are BLV, numerous eBook applications fail to provide them with the same benefits as sighted users, resulting in restricted and inequitable access to digital resources [84]. One of the widely used formats for eBooks is EPUB format. EPUB is used for representing newspaper articles, educational materials, and scientific publications. The format is designed to be easily readable on a variety of devices, such as mobile devices, and computers. In comparison to other formats like Word and PDF, this format offers a distinct advantage by supporting dynamic content, reflowable text, and adaptability to various screen sizes. Moreover, it can include text, images, links, and other multimedia elements, enhancing the overall reading experience.

Numerous studies have investigated how eBooks can be made accessible to blind people. Some of the approaches discussed the possibility of making EPUB accessible via traditional methods used by blind individuals, such as one-line Braille displays and screen readers. These methods depend on converting the information into one-dimensional data that can be accessed solely by audio or a combination of audio-Braille feedback. However, screen readers often fail to deliver the structural information such as text size, spacing information, and relative positions that may contribute to the overall understanding of the document and the overall reading experience [85]. Additionally, some investigations showed that this knowledge about the spatial layout could enable people who are BLV to collaborate and co-author effectively with sighted individuals [7].

Improving the accessibility of EPUB files has been a focus of many researchers aiming to enhance the reading experience for blind users. Bartalesi et al. [86] addressed this challenge by identifying key limitations in how screen readers convey information about images and tables, particularly how screen readers read alternative text seamlessly within the main text. Therefore, they proposed a solution to this issue, by adding hidden tags preceding various elements such as titles, tables, and lists within the EPUB format. This approach enhances accessibility by providing the user with the element-type information before it is read out by the screen reader. The results of evaluating this enriched EPUB format in a survey with 18 blind participants showed improvement considering the detection of images and tables, however, some improvements were noted for future eBook readers to further improve the accessibility. One recommendation is the incorporation of a navigation structure that enables users to navigate through content section by section. Additional features include easier and quicker access to the table of contents, the option to toggle the visibility of complex data elements such as tables and images upon user request, and the use of the content structure for navigation through the table of contents and headings. Further suggestions encompass the ability to semantically detect element types from tags and attributes.

In a survey by Leporini et al. [87] involving 75 blind participants, their preferences for studying with different types of books were explored. The results showed that 56 participants preferred eBooks over audiobooks for studying, and 92 expressed interest in a new eBook reader with improved reading capabilities. The survey also highlighted significant usability challenges, such as difficulties in managing notes and navigating sections efficiently. While mobile devices are valued for their portability, they often lack accessible editing features, making tasks like annotation and searching cumbersome. Participants emphasized the need for functionalities such as efficient navigation through pages, chapters, and paragraphs, alternative text for images, and features like bookmarking, text highlighting, and exporting content to files or email.

Kim et al. [88] presented another approach of which blind users can read EPUB and Digital Accessible Information System (DAISY) documents using 2D tactile Braille displays. The system consisted of an application that ran on a smartphone, which processed the eBook file and also handled the user interactions. By using this application, the user could navigate in the file using their phone and accordingly, the displayed data on the smartphone is converted into tactile format and can be displayed on the connected tactile display. By relying solely on the smartphone for user interaction, the researchers did not explore opportunities to utilize some of the currently available tactile display capabilities for direct touch-based navigation or interaction, which could enhance usability and accessibility. Furthermore, the approach was not evaluated with blind users to gather insights into the system's practicality and effectiveness.

3.1.2 Document Layout Analysis Methods

DLA refers to the process of identifying and categorizing the structural components of a document, such as titles, paragraphs, images, tables, and captions, based on their visual and spatial arrangement on the page. One of the most important applications of DLA in this context is improving the accessibility of PDF documents. PDF is a widely used format for digital content, including scientific papers, legal documents, and official reports. While PDFs preserve visual consistency across platforms, their fixed-layout nature often lacks semantic structure. Many documents are missing key accessibility features, such as tagged content, reading order, and alternative text. As a result, navigation and interpretation become difficult for users who rely on screen readers.

To address these challenges, DLA methods aim to recover the structure of PDF files by analyzing their visual and spatial characteristics. Traditionally, DLA was employed in enterprise applications, where businesses require efficient processing of large volumes of documents to perform tasks, such as information retrieval and key-value extraction [89]. However, recent advances have redefined DLA as a visual object detection or segmentation task, using CNNs, including the YOLO model family [90]. In addition to CNN-based approaches, transformer-based models, such as Di [91], demonstrated strong performance by leveraging image transformer architectures tailored to document layouts. Multi-modal models like LayoutLMv3 [92] add a step further by integrating text, layout, and visual cues into a unified framework for document understanding.

This methodological progress has been accompanied by the development of large-scale benchmark datasets. PubLayNet [93] and DocLayNet [94] offer extensive annotated corpora for training and evaluating DLA models using visual and spatial features. Other datasets, such as FUNSD [95] and ReadingBank [96], include textual annotations, layout metadata, and reading order, allowing for more holistic document representation.

However, in daily life, especially for individuals who are BLV, documents beyond traditional structures are frequently encountered. These can include magazines, flyers, or other designs where layouts deviate from common structures, often incorporating creative design elements. Existing datasets in the field, such as DocLayNet [94] and PubLayNet [93], focus solely on structured documents, which limits model reliability and robustness in real-world scenarios.

On the other hand, current accessibility approaches focus primarily on element-wise accessibility. For instance, utilziation of large vision-language models to summarize and understand documents [97]. Wang et al. [98] applied specialized models to convert PDF metadata into HTML, demonstrating strong performance in extracting and presenting document structures. However, the approach is computationally intensive due to the reliance on multiple models and is limited to PDFs with a text layer, restricting its broader applicability. While these models are valuable for reading documents and improving accessibility, they do not fully support users who are BLV in interacting with and exploring different document sections independently.

3.1.3 Digital Graphical Formats: Raster and Vector Graphics

Digital graphical information can be broadly categorized into two formats, raster and vector graphics. Raster graphic formats such as *PNG* and *JPEG* represent images by storing the color value of each individual pixel. As a result, the file size can become quite large, prompting the use of compression algorithms to reduce storage requirements. Depending on the type of compression, lossy or lossless, the retrieved image may either retain all original data, as in PNG, or lose some information, as in the case of JPEG.

In contrast, vector graphics represent images as a collection of geometrical shapes with attributes such as position, size, and color ([99]). These shapes are defined mathematically using vectors within a Cartesian coordinate system. Common vector formats include Encapsulated PostScript (EPS), Drawing Exchange Format (DXF), and SVG. A key advantage of vector graphics over raster formats is their scalability: because the shapes are described mathematically, they can be scaled to any size without loss of quality [99]. Raster images, on the other hand, are resolution-dependent and tend to degrade when resized.

SVG is one of the widely used vector formats, developed by the W3C. SVG is an XML-based format that accurately captures the structure and geometry of graphical elements such as lines, curves, shapes, text, and even embedded raster images. Thanks to its semantic structure, SVG improves accessibility: graphical content can be indexed by search engines and read by screen readers. The format also supports metadata, such as titles and descriptions, making it easier to search and interpret graphical content, particularly in web environments [100].

To support devices with limited resources such as mobile phones, a lighter profile called SVG Tiny (SVGT) was introduced. The first version, SVG Tiny 1.1, released in 2003, was based on SVG 1.1 and removed several features, including scripting, and elements like <*symbol*>, <*marker*>, <*pattern*>, and <*filter*>, among others. It also excluded advanced styling features such as gradients and transparency. In 2008, an updated version called SVG Tiny 1.2 was released as an extended subset of SVG Full. This version reintroduced some previously excluded features, such as scripting support and more advanced text styling, as summarized in Table 3.1.

Feature / Element	SVG Full 1.1	SVG Tiny 1.1	SVG Tiny 1.2	Feature / Element Use
`symbol`	Yes	No	Yes	Reusable graphics
`marker`	Yes	No	Yes	For arrowheads, line ends
`switch`	Yes	No	Yes	Conditional rendering
`textArea`	No	No	Yes	Wrapped multiline text
`handler`	No (JavaScript used)	No	Yes	XML Events for interaction
`audio`, `video`	No	No	Yes	Multimedia support
`foreignObject`	Yes	No	Yes	Embeds HTML, MathML, etc.
`solidColor`	No	No	Yes	Solid fill paint server
`viewBox` on <use>	No	No	Yes	ViewBox on reused elements
Scripting	Yes (JavaScript)	No	Limited (XML Events)	Varies by version

Table 3.1: Features with different levels of support in SVG Full 1.1, Tiny 1.1, and Tiny 1.2.

Scan Conversion Process. In order to display vector graphics on digital screens, they have to rasterized or converted to grids of pixels or dots. This process of translating the vector-based representation into pixels-based representation is called scan conversion or rasterization. There exist different algorithms for conducting this conversion, for example for converting lines, polygons, curves, etc. into pixels. Several algorithms exist for scan converting different geometrical shapes, such as:

1. **Digital Differential Analyzer (DDA) Algorithm:** An algorithm that works by incrementally calculating intermediate points between two endpoints using floating-point arithmetic. The algorithm steps along one axis (usually x) and computes the corresponding y values by using the line slope. Although it's easy to implement, the DDA involves floating-point calculations which may be slower on some hardware.

2. **Bresenham's Line Algorithm:** A more efficient and widely used line drawing algorithm that uses integer arithmetic instead of floating-point, which improves speed and accuracy on digital devices. The algorithm determines the closest pixel to the theoretical line at each step by incrementally evaluating an error term, minimizing visual artifacts such as jagged edges (aliasing).

3. **Scanline Polygon Fill Algorithm:** An algorithm for filling geometrical shapes by determining intersections of the polygon edges with each horizontal scanline. This method efficiently fills polygons by identifying pixel ranges inside the polygon per scanline, which is especially useful for solid shapes and graphical objects.

4. **Midpoint Circle Algorithm:** An algorithm for drawing circles and arcs. Similar to Bresenham's line algorithm, it uses incremental integer calculations to determine the points closest to the ideal circle path, exploiting the circle's symmetry to reduce computation.

3.2 Tactile Document System for PDF Format

This section presents a system for automatically extracting layout information from various types of documents and presenting it in an accessible format for individuals who are BLV using 2D refreshable tactile displays. To achieve this, DLA approaches were employed to automatically retrieve document structures, using a benchmark dataset specifically developed for this task. The extracted information is then presented to the user by presenting a design of a TUI to convey document structure through 2D tactile displays. The system implements multimodal interactions, allowing users to explore documents interactively through both tactile feedback and audio.

The key contributions of this section are the following:

- A method to automatically extract document layouts, and a new dataset comprising common complex layouts, including slides and newspapers.
- The design of a TUI for displaying documents on 2D refreshable tactile displays to enable users who are BLV to navigate and explore complex document layouts through haptic and button-based interactions and auditory feedback.

This section is based on a publication in MDPI Multimodal Technologies and Interaction (2024) [2]. Some texts remain unchanged from the original publication.

3.2.1 Overview of the System

The system consists of two main modules, (a) the *layout extraction module*, and (b) the *tactile representation module*. The layout extraction module is responsible for analyzing documents in PDF format and extracting the metadata required to create a tactile representation of the document. This module runs on a separate server and incorporates a trained object detection based on the YOLOv10 model [101], to segment each page and identify key visual elements. It retrieves spatial metadata, such as bounding boxes for each element, and applies OCR techniques to extract the associated text. To preserve document semantics and reading flow, the module also infers the reading order of the extracted elements. Additional processing steps use ChatGPT [102] to enhance the extracted metadata by adding information related to the reading order of the document and summarizing the element content.

Once the metadata is extracted, it is passed to the tactile representation module. This component runs on the 2D tactile display device and converts the metadata into a format suitable for tactile rendering. It manages user interactions via both touch and button inputs, and provides audio feedback to support multimodal document access.

Figure 3.1 presents a simplified UML sequence diagram of the system's workflow. It illustrates how a PDF file is uploaded by the user and sent to the server, where the layout extraction module performs segmentation, text recognition, and metadata enhancement. The resulting metadata is then transmitted to the local device, where the tactile representation module renders it in a tactile format. The user interacts with the document using touch gestures or buttons, and the system responds with both tactile and auditory feedback. This sequence ensures that each document is pre-processed remotely, while the interaction and rendering occur directly on the tactile display, keeping the interface responsive and consistent.

The following sections provide a detailed explanation of the two system modules.

3.2.1.1 Layout Extraction Module

(a) Model Training and Dataset. To enable effective document layout extraction, a model requires training on a diverse and representative document layout dataset. Among the primary datasets in this field is DocLayNet [103],

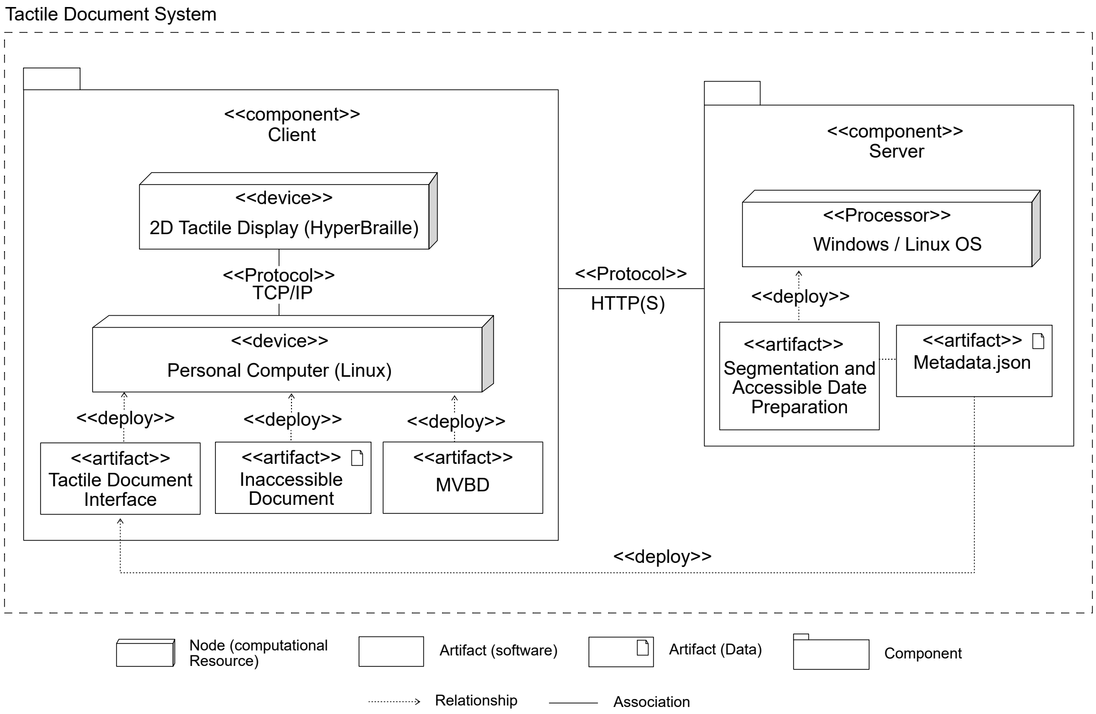


Figure 3.1: UML deployment diagram showing the architecture of the tactile document system.

a comprehensive collection covering categories such as financial reports, scientific articles, laws and regulations, government tenders, manuals, and patents. These categories share a standardized layout structure across sources; for instance, scientific articles from various publishers tend to exhibit similar sectioning and design. However, In real-world scenarios, layouts are often much more varied and may include visually complex documents like magazines, which are typically crafted by designers using multiple layers and artistic elements.

To address this gap, a new dataset, Artistic Document Layout *(ArtDocLay)* was created. The dataset was initially curated by crawling 1,017 documents from Commoncrawl repository [104] using a keyword-based filtering approach to capture eight unique artistic categories, as shown in Table 3.4. Afterwards, manual selection of 37 documents from each category was done, ensuring each document showcased unique and varied layouts, even within individual pages. Following DocLayNet's annotation guidelines, a total of 324 images were annotated and resulted in 3,526 bounding boxes. Table 3.4 provides statistical insights into the new dataset. The data was divided to training, validation, and test splits with a 70:10:20 percent respectively.

Model	mAP50	mAP50:95
YOLOv10x	31.9	19.5
YOLOv10b	29.5	17.3
YOLOv10l	36.7	19.3
YOLOv10m	33.0	17.7
YOLOv10n	30.4	18.6
YOLOv10s	31.8	18.4

Table 3.2: Performance of different YOLOv10 models trained on *DocLayNet* [2].

Model	mAP50	mAP50:95
YOLOv10x	56.6 (+24.7)	31.5 (+12.0)
YOLOv10b	55.7 (+26.2)	34.4 (+17.1)
YOLOv10l	60.5 (+23.8)	33.7 (+14.4)
YOLOv10m	53.7 (+20.7)	30.6 (+12.9)
YOLOv10n	64.8 (+34.4)	29.0 (+10.4)
YOLOv10s	52.8 (+21.0)	29.6 (+11.2)

Table 3.3: Performance of different YOLOv10 models fine-tuned on *ArtDocLay* and the improvement to in comparison to the *DocLayNet* shown in blue [2].

Category	**# Books**	**# Images**
Brochure	7	44
Newspaper	5	48
Books	3	84
Magazine	4	52
Slide	4	79
Poster	2	2
Flyer	6	11
Infographic	4	4
Total (8 categories)	**35**	**324**

Table 3.4: Artistic documents in the new dataset (*ArtDocLay*) with book and image counts [2].

To extract the layout of documents, object detection models were utilized. A crucial requirement for the model selection is the ability to operate in real-time and perform efficiently on low-power devices in order to run the segmentation directly on 2D tactile displays. For this purpose, the YOLO family was found to be suitable, given its balance of speed and resource efficiency.

The latest version, YOLOv10, as provided by Ultralytics [1] was used for the detection. YOLOv10 is a single-shot detector, which makes it distinct from prior versions by incorporating NMS-free dual label assignments and a holistic efficiency-accuracy driven model design. This design choice reduces computational redundancy, enhancing both speed and accuracy [90]. As the YOLO models are available in different variants, all the YOLOv10 variants were tested to determine the best perfrmanc. The variants from YOLOv10-x (X-Large, with 29.5M parameters) to YOLOv10-n (Nano, with 2.3M parameters). In the first stage, all models were trained on the DocLayNet dataset for 100 epochs, starting from COCO-pretrained weights available by Ultralytics. In the second stage, the model was fine-tuned by training it on the new dataset, using a training split for 10 epochs, using zero warmup for a smoother transition and a higher learning rate of 0.01 to accelerate learning on the new dataset.

Table 3.3 presents the test performance on the artistic dataset, highlighting the limited performance of models trained solely on the DocLayNet dataset, shown in Table 3.2, which is primarily suited to structured documents. This limitation is particularly relevant for blind users, as higher error rates can lead to frustration, such as when an element labeled as an image caption turns out to be a table or when captions go undetected entirely. The ArtDocLay dataset that was used to finetune the model demonstrated an improvement, with YOLOv10-X showing a gain of +24.7 mAP50 and +12.0 mAP50:95 over DocLayNet alone. Qualitatively and quantitatively, this improvement means bounding boxes are more accurately aligned with objects in the page, both in location and class. This alignment facilitates better reading order and element identification, reducing hallucinations and enhancing accessibility for blind users. For inference speed, the YOLOv10-X variant achieved a runtime of approximately 6 ms on an NVIDIA A40 GPU. Finally, elements with confidence scores of greater than 0.5 were stored in the results file. These predictions are then processed in subsequent steps to establish reading order and generate tactile layout representations, as detailed in the following sections.

(b) Annotations Post-Processing Steps. After segmenting the PDF documents using the trained model, a JSON file is obtained including the annotation of each element existing in each page in the document. These annotations are represented in bounding boxes that surround each element in the document. The bounding box information include the coordinates and the size of the element. Additionally, the type of the element is extracted depending on the type of dataset used for training. For example according to the used dataset in this case, there exist 12 categories or labels that can be extracted from PDF documents. Following the extraction of the annotations, some

[1] `https://github.com/THU-MIG/yolov10`

Detected Subclasses	**Mapped Class**	**Tactile Representation**
Document title, section title, header	Title (t)	⠞
Paragraph, footer, caption, page number, list-item	Text (x)	⠭
Table	Table (b)	⠃
Equation, code	Math (m)	⠍
Figure	Image (i)	⠊

Table 3.5: Detected elements using the trained model and their tactile representation.

post processing steps are required to prepare the annotations in a suitable format to be displayed on 2D tactile displays. For example, in order to simplify the representation of the document elements, the categories obtained from the YOLO model, which are ten categories, are mapped into five clusters, title, text, table, math and image, as shown in Table 3.5.

After extracting the coordinates of each element on the page, sub-images are generated for each text element by cropping the original document image accordingly. For non-text elements such as figures, a separate subdirectory is created, containing the cropped images to be used in subsequent processing steps aimed at rendering them on the 2D tactile display. The final annotation object consists of the following information:

1. **Bounding Box:** An array that includes the top left corner coordinates, as well as the width and height of the element.
2. **Center Coordinates:** The center coordinates of the bounding box corresponding to the element.
3. **Category Id:** The category id of the element corresponding to the type (e.g. text, table etc.).
4. **Path:** The file path, in case of image element.
5. **Text:** The extracted text from the element using OCR.
6. **Image Id:** The image id corresponding to the page number.
7. **Reading order:** The reading sequence of the element.

(c) Document Sub-elements Adjustments. Following the preparation of annotations, several refinements are applied to enhance the accessibility of the document's tactile representation. First, any leading or trailing empty space present in the original PDF, which often resulting from page margins or formatting artifacts, is removed. Eliminating these unnecessary regions helps to optimize the use of space on the 2D tactile display and reduces potential confusion for users. In addition, the vertical alignment (y-coordinates) of text elements that are positioned closely together is adjusted to ensure they appear on the same line. This step minimizes the occurrence of densely packed horizontal lines in the element identifier column displayed on the screen to improve the clarity of the tactile layout and help reduce the cognitive load on users during exploration.

(d) Reading Order. For readers who are BLV, a logical reading order is essential for understanding document content as intended. To establish this, first the page image is annotated with bounding boxes, each labeled with an ID in the top-left corner, as shown in Figure 3.3 (a). Then OCR techniques are used to extract text from each bounding box. For this step, Tesseract OCR [105] is used due to its robustness in recognizing printed and scanned text. The page image is first cropped according to the coordinates of each bounding box, isolating individual regions classified as textual elements (e.g., titles, section headers, body text, footnotes). These cropped regions are then passed to Tesseract for text recognition. Non-textual elements, such as figures and charts, are paired with their captions to retain context. Then GPT-4 [102] is promted with the annotated layout and OCR data, asking it to arrange elements into a coherent reading sequence based on spatial and textual cues. To accomplish this, the model is provided with a prompt that summarized the task as follows:

"Your task is to reorder the bounding box IDs to reflect the natural reading flow of the document page based on the content and the spatial location of the text. You will be provided with an image of the document where bounding boxes are drawn, along with metadata describing each bounding box, including coordinates, class name (e.g., 'Title', 'Text', 'Section-header'), and OCR-extracted text. Please return the bounding box IDs in the correct reading order as a JSON array."

The final reading order, along with spatial and textual content, is stored in a JSON file that is later passed to the tactile UI module.

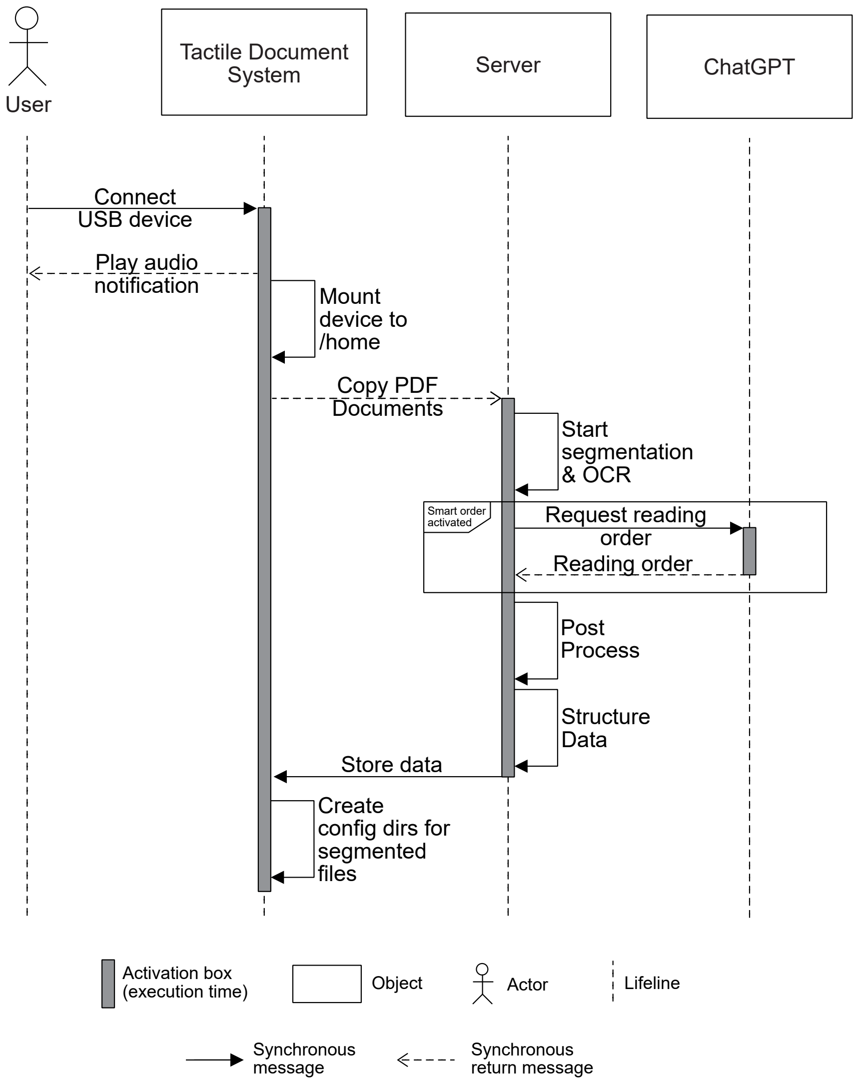
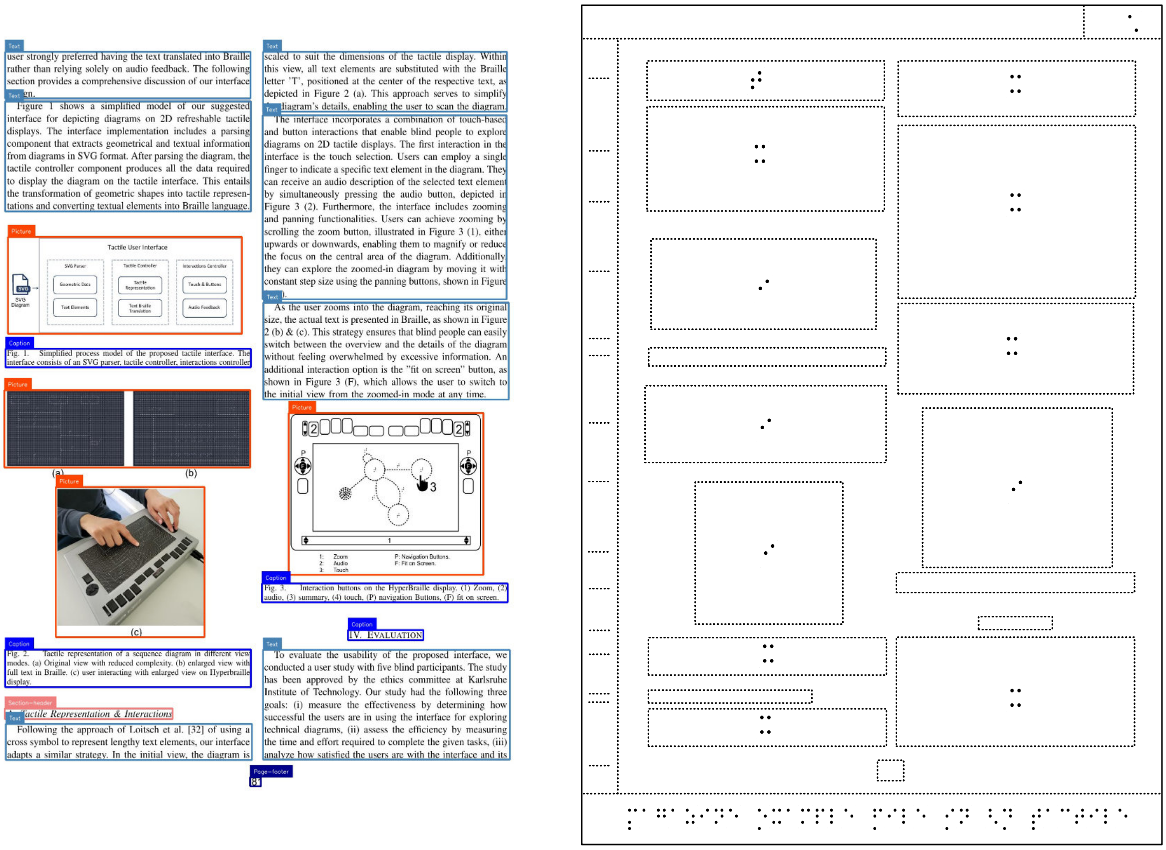


Figure 3.2: Sequence diagram showing the processing of converting PDF documents into a tactile format and how the communication is handled with external objects, such as the processing server and ChatGPT.

3.2.1.2 PDF TUI Design

The TUI consists of two main components, the first component represents the mechanism for displaying the document on the display. The second component is the interactions available in the interface. For both components, previous analysis of exiting TUIs discussed in Section 2.7.1 is utilized as a guideline for representing the information, as well as insights gained through a participatory process involving collaboration with a blind user. This collaborator, who has extensive experience using assistive technologies, provided iterative feedback on how documents should be structured in a 2D tactile format and contributed to defining the core interaction concepts needed for effective navigation and exploration. Their input served as a foundation for designing an interface that aligns with the practical needs and expectations of users who are BLV.

The interface was implemented and tested on the HyperBraille display [69], which, was the only available 2D refreshable tactile display at the time of development. The device features a grid of 60×104 taxels with a resolution of 10 dpi and supports touch input. As shown in Figure 3.5, the device also includes 19 physical buttons: navigation buttons on either side of the tactile surface and a scroll button below it. The HyperBraille operates through an API that allows developers to control pin actuation and assign button functions.



(a) (b)

Figure 3.3: An example of a document at the various stages of the system pipeline: (a) Following document segmentation, bounding boxes are generated for each element, with ids assigned to each bounding box. (b) The tactile representation of the document in the TUI, by presenting the bounding boxes resulting from the trained model in a tactile format with Braille letters at the center and the element identifiers column shown at the left of the view.

This collaboration resulted in two prototypes of the user interface. The first prototype aimed to analyze the representation of the metadata extracted from documents using the trained model, maintaining the original document layout. Therefore, the first prototype that was designed was a static version of the TUI which did not include any interaction possibilities.

As for the representation of the document, two concepts were developed. The first one involved placing a Braille character at the center of each document element. For example, a paragraph was marked by the Braille letter "x," while a title was represented by the letter "t," as detailed in Table 3.5. The second concept included presenting the whole bounding box in a tactile format using a scale factor that allows the page to fit on the width of the tactile display, while enlarging the length of the page. This decision was made to avoid confusion if the document was scaled on both width and height, based on the feedback obtained from the evaluations of existing TUIs in the literature shown in Section 2.7.1.

This first prototype was then presented to the blind collaborator on the Hyperbraille display and their feedback was asked on improving the representation and accordingly, defining fundamental interactions that allow users to navigate, read and explore any PDF document. Regarding the representation, the collaborator preferred the version of the document with the bounding boxes. Regarding the interactions, the collaborator suggested to implement the following four modifications:

1. Implementing all interaction buttons symmetrically on both sides of the device to allow the users to explore the document using both hands and avoid losing the orientation at any time when using the buttons. This would also enhance the accessibility for left and right handed users.
2. Integrating audio feedback to provide the text of each element when needed.
3. Providing the user with an acoustic feedback while using the navigation buttons to signal the occurrence of a change.
4. Including a feature to offer additional details, such as the number of columns, element types, and document format (e.g., paper, slide, receipt), upon request.

After the first evaluation, a second prototype of the interface was designed to include the interaction methods for navigating and exploring and also to incorporate the interactions suggested by the collaborator. The design of the second prototype was guided by Shneiderman's VISM [80] for information visualization, shown in Section 2.7.2.1. Although VISM is initially intended for visual interfaces, prior research has successfully adapted its principles for designing audio interfaces for blind users [106]. Therefore, the VISM's guidelines were analyzed and explored if they could also be applied to the design of TUIs that can run on 2D tactile displays. The design of the second prototype implemented the three VISM principles, which are the overview, filtering, and details on demand. The following section describes the implementation of the three principles in detail.

Overview Principle: The overview principle is realized in the interface through two distinct overview modes: the simplified view and the bounding boxes view, illustrated in Figure 3.4 (a) and (b), respectively. The simplified view mode depicts three main components on the tactile display, as shown in Figure 3.4 (a). The initial component is the "Element Guide", which is a vertical rectangular region where with horizontal lines. These lines indicate the existence of a document element, such as text, title, table, math, and image, at that specific level. These lines align with the y-values of the bounding box centers that hold each element. The second component is the "Class Identifier" area, where a Braille character is placed at the center of the bounding box. This character represents the layout class, for example, "x" for a text element. The last part is the "Divider Line," which separates the previously mentioned sections, aiding users in distinguishing between the first two components. The bounding boxes view mode, as shown in Figure 3.4 (b) displays bounding boxes around each element in the document page, representing them as rectangles with dimensions corresponding to the width and height of the respective element. Additionally, in each view mode, two sections are always present on the screen: the header section and the footer section, as depicted in Figure 3.5 (6) and (8), respectively. The header section shows the current page number, while the footer

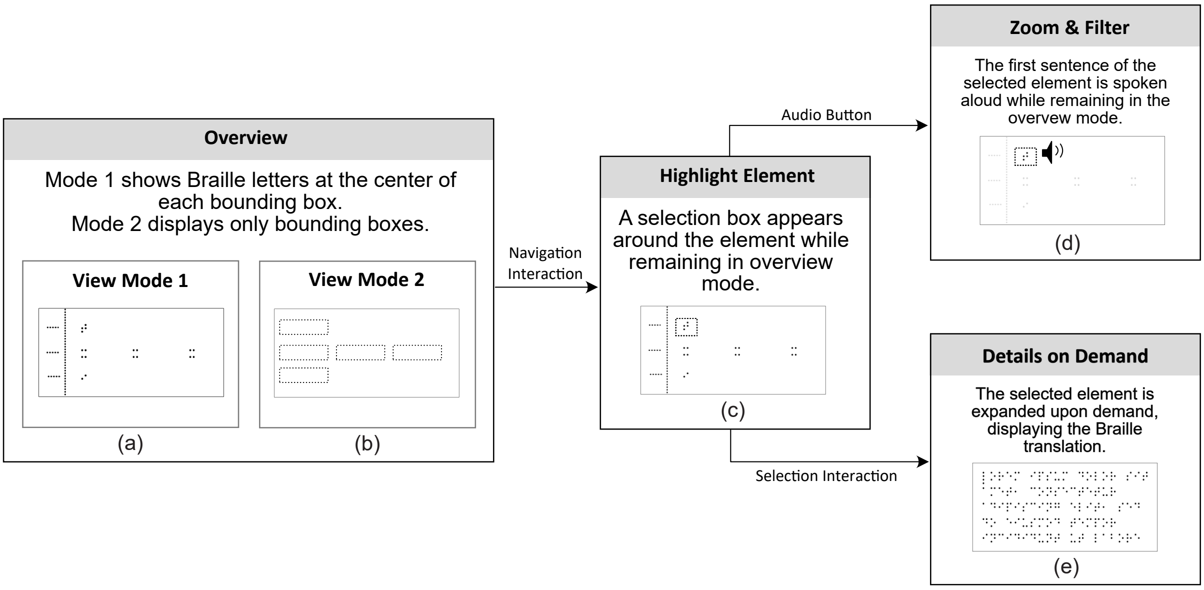


Figure 3.4: The different views available in the tactile document interface, based on the VISM principles. (a) Simplified overview mode. (a) Bounding boxes overview mode. (c) Selection of an element to explore through navigation buttons or touch. (d) Zoom and filter view. (e) Details-on-demand view.

section shows the file name. The goal of the two view modes is to provide users with a quick overview of the document, enabling them to easily visualize the different elements present.

Filtering Principle: The zoom and filter principle is defined in the VISM as a method for reducing the complexity of the data representation by removing unnecessary information from the user's view, enabling focused exploration of relevant details. In the interface, this is implemented by allowing users to select specific elements within a document while in overview mode, as demonstrated in Figure 3.4 (d). Upon selection, users receive brief acoustic feedback, consisting of the first sentence from the chosen element, providing concise information without needing to switch to a detailed view. This approach helps users grasp key content quickly while maintaining their overall orientation in the document.

Details-on-demand Principle: The principle of details-on-demand is realized by allowing the user to select any element in the overview mode, as shown in Figure 3.4 (c), and move to another detailed view. The detailed view, as shown in Figure 3.4 (e), displays the selected element of interest on the display. The Braille translation will be displayed if the selected element is a text. If the element is an image, the alternative text will be presented. If the alternative text is unavailable, a standard text message informs the user that this is an image without alternative text.

3.2.1.3 Interaction Concepts

The interface was designed with fundamental interactions that facilitate document exploration and transitions between the various available view modes. The interaction concepts were implemented using only the buttons available on the HyperBraille to ensure accessibility for any 2D tactile display that lacks touch capabilities. The interactions are only available in the simplified overview mode, where users can navigate between document elements and access detailed content. This decision was made to reduce cognitive load and avoid clutter in the bounding boxes view, which serves primarily as a structural reference.

The tactile and audio feedback was intended to help users develop a comprehensive understanding of document structure. For instance, in overview mode with Braille letters, tactile feedback conveys spatial relationships, supporting users in forming a mental map of the document's layout. Additionally, audio signals complement specific interactions, such as distinct sounds when navigating between elements and a crash sound indicating the document boundary. Together, these cues provide clear structural information, helping users maintain orientation within the document.

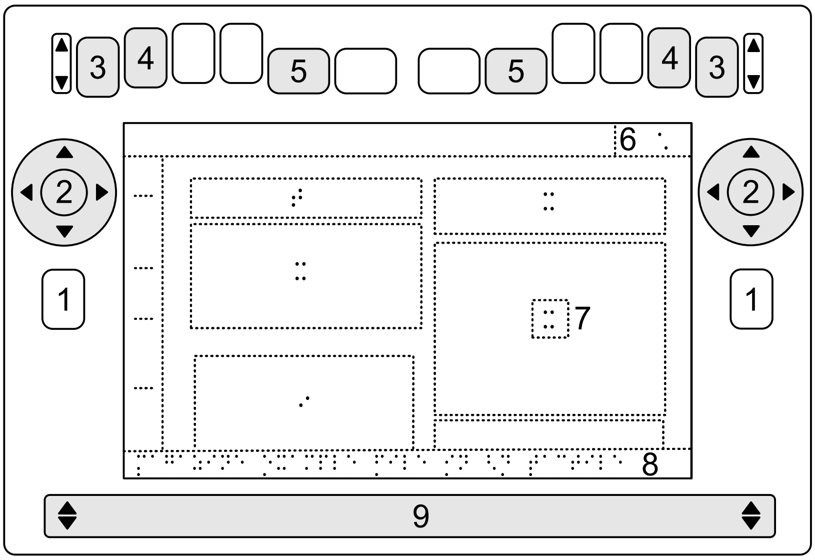


Figure 3.5: The interactions available in the tactile document interface and the corresponding buttons used on the HyperBraille display. (1) back button, (2) Navigation controls, (3) audio feedback, (4) view mode button, (5) help buttons, (6) page number, (7) document element with a selection box, (8) file name footer, (9) page navigation button.

1. **Selection and Navigation Using Buttons:** In order to allow the user to navigate through the different elements in the document, selection and navigation concepts were implemented using the navigation buttons shown in Figure 3.5 (2). By default, the top most element in the document is highlighted by displaying a tactile rectangle around the element identifier, as shown in Figure 3.5 (7). The user can navigate to the next elements in the document by pressing the navigation buttons (right, left, up, down). An auditory signal is played every time a new element is highlighted to notify the user that an element has been selected. If the user attempts to navigate beyond the end of a row, a distinct audio signal resembling a crash is emitted to indicate that further navigation in this specific direction is not possible. Pressing the selection button again expands the highlighted element, displaying the full text in Braille, or in case of images, the alternative text is displayed in Braille.

2. **Audio Feedback:** In the simplified overview mode, when an element is highlighted, the user can listen to the first sentence within that element by pressing the audio buttons, as shown in Figure 3.5 (3). This functionality is designed to assist blind users in skimming through a document, providing brief information about the text within the element without losing their sense of the overall layout. Similarly, if the same button is pressed while in the "Details on Demand" view mode (after selecting an element and displaying its content), the user can listen to the full text displayed.

3. **Return to Overview Mode:** Switching back from the "Details on Demand" view, where the text element is expanded, to the overview is done by clicking the back buttons shown in Figure 3.5 (4).

4. **Bounding Boxes Overview Mode:** The user can switch to the bounding boxes overview mode by pressing the overview mode button, shown in Figure 3.5 (4). However, this mode is static, meaning the user cannot select or navigate between different elements.

5. **Scroll Pages:** By pressing the scroll bar in Figure 3.5 (9) once, the user can scroll up and down the page. If the user holds the scroll bar longer, they can navigate to the next or previous page.

6. **Extra Information:** If the user presses the help buttons, as illustrated in Figure 3.5 (5), the user can obtain extra acoustic information about the file's name, the current page, and the number and types of the elements currently visible on the screen. For instance, when the user clicks the help button, the document shown in Figure 3.6 (a) would generate the following spoken text: *"This is page 1 in document PDF File 1. There are currently five elements displayed on the screen. The elements include one title, three text, and one image."*

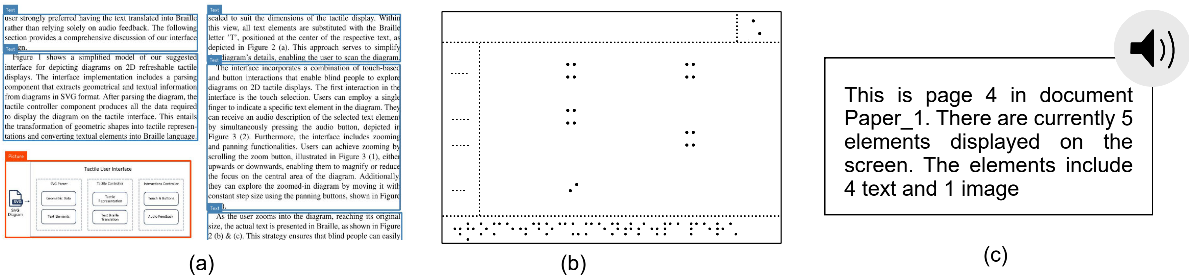


Figure 3.6: (a) Section of a document to be represented on the 2D tactile display. (b) The same section of the document represented in the overview mode using the interface. (c) The corresponding auditory information given to the user after clicking the help button.

3.2.2 Evaluation

A preliminary study was conducted with the six participants (theree blind users and three blindfolded) to evaluate the second prototype of the interface. The blind folded participants were the first users to test the interface to make sure the interactions are functioning well and to assess the general usability of the interface and detect major issues with the interface. The general aim of the study was to explore if the participants who are BLV can use the new TUI to access complex documents, such as magazine articles with multiple columns and analyze how intuitive the interactions are. Additionally, the user study was required to assess the effectiveness of the VISM approach for presenting documents on 2D refreshable tactile displays. Therefore, the following three goals were defined for the study: (a) determine how useful the interface is for reading and skimming documents with complex layouts (two or more columns). (b) Assess the effect of using the interface on the efficiency of reading and skimming compared to conventional aids such as screen readers. (c) Analyze the satisfaction of the participants with the interface and its interactions. The second and third goals were only aimed at the blind participants in the study.

3.2.2.1 Participants

The participants were recruited through the university mailing lists. Table 3.6 shows the demographic data of the participants. All participants who are BLV had prior experience with 2D tactile displays and depended on screen readers for reading documents and could read Braille and had a high level of education, at least a bachelor's degree or higher. All blindfolded participants were also individuals chosen due to their familiarity with 2D tactile displays and to at least have tested such devices before. Two of the blindfolded participants (P4, P6) had previous experience in designing software for such devices.

3.2.2.2 Procedure

Each study lasted 60 minutes and included one participant and the moderator. The participant provided their informed consent at the beginning of the study, in accordance with KIT university's ethical guidelines. Each study consisted of four sessions: the first session was an introductory session, during which each participant received a training document containing step-by-step instructions for 15 minutes, guiding them on how to use the interface. In

Participant	Vision	Age / Gender	Reading Assistive Tools
P1	Blind	48–57 / M	Screen reader / 1D Braille display
P2	Blind	23–32 / M	Screen reader / 1D Braille display
P3	Blind	23–32 / F	Screen reader
P4	Blindfolded	18–22 / M	-
P5	Blindfolded	23–32 / F	-
P6	Blindfolded	23–32 / M	-

Table 3.6: Demographic information of participants in the user study for testing the tactile document system.

the second session, the participant was provided a four-column magazine article [107] to read on the tactile display using the TUI. Additionally, a third session was conducted with participants who are BLV only. In this session, the participants were given another magazine article [108] to read using NVDA [47] screen reader on a computer.

Following session two and three, the participant was asked to perform the following tasks:

- **Task 1:** Skim the document and give a quick summary of the topic and the main key points.
- **Task 2:** Answer a question about certain information in the document. Document one [107]: How does the writer stay updated on the rapidly occurring changes?. Document two [108]: Why do some individuals prefer to be anonymous online?)
- **Task 3:** Explain the structure of the document.

For the participants who are BLV, the time was measured for the first two tasks, to compare the TUI with the typical approach of using screen readers and assess whether the 2D tactile display delivers a comparable result. For blindfolded users, timing was omitted, as their role was limited to identifying major issues with the interaction concepts.

After finishing the three tasks, participants were requested to provide their opinions on the ease of using the interface and their interactions with it. For this purpose, the participants were provided the System Usability Scale (SUS) [109] questionnaire to answer, which is a questionnaire consisting of five questions that can be used to assess the usability of computer systems.

3.2.2.3 Results

Overall, participants who are BLV did not encounter any difficulties understanding the concept of presenting documents in a 2D tactile format. They could navigate the provided document using the provided tactile UI and the available interactions. Additionally, they were able to navigate to and extract certain information in the document and answer the questions effectively. The average time required by the participants to complete task one (skimming he document and providing quick summary of the topic) was 5.7 minutes, while the average time required to finish task two (extract certain information from the document) was 1.8 minutes.

The blindfolded participants were able to complete the tasks and navigate through the first document. However, they reported losing orientation when moving between pages or reaching the end of the document, due to the lack of feedback indicating that the end of a page had been reached.

Tactile Data Representation Modes. The different view modes available in the interface were noted to be sufficient for conveying the structure of the document. This was confirmed by the ability of the participants to figure out the document type by interpreting the structure using the bounding boxes view mode. However, when the participants were asked about their preferred view mode, all participants favored the bounding boxes view over the centered Braille letter view, mentioning that it was easier to comprehend spatial arrangement. P1 and P3 suggested combining both view modes, allowing simultaneous access to bounding boxes and the central letter views, as the central letter adds extra information about the type of element represented by the bounding box. P2 answered when asked why he preferred the bounding boxes overview more: *"It made me personally quite happy because I have just seen a document again as it was there, so not just in 1D as on the Braille 1D display, but as it really is."*.

Participant P3 also confirmed that the bounding box view mode was useful in understanding the structure of the document and also added that the markings provided at the left of the display in the case of the centered Braille letter is a very useful mechanism and should also be present in the case of the bounding box view mode.

Regarding the "Details on Demand" concept, it was noted that P1 and P2 participants found the mechanism of switching from overview to detailed view to be logical. However, P1 was observed to have some difficulties while searching for specific information in the document. The participant later highlighted that knowing whether the scroll bar scrolled within the page or the whole page was sometimes confusing. Therefore, the participant suggested integrating feedback mechanisms when scrolling within the same page, as when moving between pages, such as playing two different audio signals in each case. This issue of orientation is consistent with the feedback from the blindfolded participants, who also reported losing orientation when moving between pages or reaching the end of the document due to missing cues.

Regarding the "Zoom and Filter" concept, P3 appreciated how the audio feedback is implemented in the interface, noting that hearing only the first sentence in overview mode was particularly useful. This feature helped her quickly navigate the document and skip less interesting sections.

Interaction Concepts. All participants mentioned that they prefer to have touch interactions over purely button-based navigation when accessing the document elements. Additionally, it was noted that participants did not utilize the help function while reading. When asked about this, all participants indicated that they found it unnecessary and did not feel the need for assistance.

Regarding new features, P1 suggested integrating an additional function into the trained model that would automatically generate a summary of the document, allowing users to listen to this summary with the press of a button. Additionally, P3 expressed interest in incorporating editing options within the interface, such as highlighting specific text elements and adding comments. P3 also proposed a feature enabling users to place one finger on a word, triggering audio feedback that reads only the corresponding sentence.

In the last session, BLV participants were asked to skim the second document and answer a question about its content using a screen reader. The screen reader failed to interpret the document's structure correctly, leading to an incorrect reading order. Despite this, participants were able to guess the document's topic, with an average completion time of 7.34 minutes. However, they were unable to complete Tasks two and three.

3.2.2.4 Discussion

Based on the findings of the study, presenting document layouts on 2D tactile displays shows promising potential for offering users who are BLV access to digital documents while preserving the original layout. Participants found the data representation and navigation between modes, guided by the VISM approach, logical and intuitive. However, there is room for improvement to enhance the user experience and address usability limitations identified in the preliminary study.

Optimizing View Modes for Enhanced User Experience: It was observed that all participants favored the bounding boxes view mode for understanding the document layout and structure. However, two participants noted that the alternate view mode, which featured a Braille letter at the center of each bounding box and horizontal lines indicating the presence of elements, was also beneficial for identifying and detecting the document's different elements. Based on this feedback and a suggestion from one participant, it may be valuable to combine both modes into a single view. This unified mode would display bounding boxes with Braille letters at the center while enabling users to navigate and interact with elements. Such a design could offer a more efficient and user-friendly experience.

In general, the view modes in the TUI presented in this chapter were found to effectively provide participants with information about the structure of the document, including the position and size of various elements. In contrast, participants in the study were unable to access the same information when using a screen reader. This observation aligns with the findings of Li et al. [7], which highlighted that the most significant challenge faced by participants who are BLV in their study was the inability of screen readers to convey spatial relationships between layout elements in documents.

Importance of Interaction Feedback for Improved Navigation and Orientation: The interaction concepts for navigating between document elements and switching between different view modes were shown to be generally sufficient to support exploration of complex documents which consist of multiple columns. However, it was observed that providing immediate feedback for any interaction that alters the content displayed is crucial for maintaining orientation. For instance, one participant experienced difficulties with orientation, particularly during scrolling between pages of the document or when trying to navigate to a direction where there is no element available. Therefore, it was noticed that it is essential to include audio feedback, such as an alert or a subtle sound cue to notify the user when there is any change occurring on the screen or when trying to move out of boundary. Without this, users would need to keep one hand on the display at all times to detect these changes.

This aligns with the findings of Chase et al. [110], who emphasized the need for tightly coordinated haptic and audio feedback in user interfaces. Their research indicated that haptic guidance cues effectively complemented audio feedback. The blind collaborator, during the initial phases of designing the TUI, also underscored the importance of this coordination. This suggests that integrating both feedback types in a harmonized manner is important for enhancing the user experience for blind users.

Additional Features Multiple suggestions were requested from the participants for to improve the next versions of the TUI. P3 requested editing capabilities, such as text highlighting and the ability to add comments. Given the positive feedback on the touch interaction concepts, exploring how these editing features could be implemented through touch interactions would be a valuable direction for future development. Additionally, the same participant proposed adding a feature to listen to text word by word by placing a finger on the text in the "Details on Demand" view mode. This could further improve interaction and accessibility.

In the interface presented in this chapter, a help feature was included to provide the user with extra information about the document layout. However, it was noticed that the participants did not utilize this functionality. Some explained that they were able to complete the tasks without requiring additional assistance. This suggests the need to revise the help functionality's content and presentation. For instance, incorporating a document summary, as one participant suggested, could enhance this feature's relevance and usefulness.

While the interface presented graphical information with alternative text when available, a brief placeholder indicated the presence of an image when such text was missing. Although this was not reported as a significant issue during the preliminary study, it may be because blind users are accustomed to similar limitations in screen readers and one-dimensional tactile displays. However, given the capabilities of 2D tactile displays, exploring methods for presenting the original image itself would be worthwhile. This approach could provide users additional context and a richer understanding of the content.

3.2.2.5 Improvements to the TUI Design

Based on the feedback received from the participants in the preliminary study, the following refinements were made to enhance interaction and accessibility of the tactile document UI:

1. **Touch-based navigation:** Placing one finger on the Braille letter representing the document element type and pressing a touch-activate button opens the element.
2. **Touch-based audio feedback:** Similar to the navigation concept, the user can place a finger on the Braille letter and press the audio button to listen to the first sentence of the element.
3. **Additional audio cues:** Sound signals were added to indicate when moving to other pages in the document and when reaching the end of the document.
4. **Tactile letter adjustment:** The tactile letter placed at the center of elements was removed if the bounding box was too small or had very little height, as including it in such cases could cause confusion.
5. **Combined view modes:** The two overview modes, shown in Figure 3.4, were combined into one view mode containing both the bounding boxes and the Braille letter at the center, as shown in Figure 3.3.

3.3 Tactile Document System for EPUB Format

Another format of documents which is commonly used for eBooks is the EPUB format. Unlike PDFs, which follow a rigid visual structure, EPUB documents are built to be flexible and reflowable by storing the data in HTML and CSS formats, to adapt the presentation of the data based on screen size or user preferences. This section presents the design of a TUI and outlines the interaction concepts implemented to support EPUB document exploration using both touch and buttons on 2D refreshable tactile displays.

The contributions of this section include:

- A design of a TUI to represent eBooks in EPUB format on 2D refreshable tactile displays.
- Interaction concepts incorporating both touch- and button-based inputs, developed through insights from existing literature.
- Findings from a preliminary study with two blind participants to evaluate the TUI.

This section is based on a publication in Pervasive Technologies Related to Assistive Environments PETRA (2025) [3]. Some texts remain unchanged from the original publication.

3.3.1 Overview of the System

The tactile EPUB system consists of two components. The first component is the parsing and pre-processing unit responsible for the extraction of the data in the EPUB format. The second component is the TUI which implements the representation view modes and the audio feedback and haptic interactions. The interactions implemented in the interface cover some of the recommendations of Bartalesi et al. [86] and Leporini et al. [87]. The recommendations include the implementation of different schemes for navigation, such as the possibility to navigate eBooks by chapters, paragraphs or sections. Additionally, providing the users with list of content page which can be used for navigation.

3.3.1.1 Parsing and Pre-processing Unit

The component is responsible for handling the different file formats embedded within the EPUB file, which are the following:

1. The first file format is an eXtensible HyperText Markup Language (XHTML) document, which contains the primary document content.
2. The second file format is a Cascading Style Sheet (CSS) file that defines the layout and formatting of the content, specifying the sizes and positions of text, images, and other elements. Both file formats are parsed using the litehtml library [111].
3. The third file format for graphics is the PNG format which is parsed using OpenCV library [112].

After parsing, some adjustments are made to the files for a better tactile representation. For example, all images are resized to fit the dimensions of the 2D refreshable tactile display, with the colors reduced to black and white. Additionally, the distances between all elements are modified to ensure adequate spacing, preventing overlap or elements being too close to each other.

For the XHTML file, an additional hidden tag is added to mathematical equations written in LaTeX format to distinguish them from standard text to enhance accessibility. Afterward, text elements from each page are translated into six-dot Braille on a word-by-word basis using the Liblouis library [113]. Words are evaluated if they fit within the current line to avoid splitting, ensuring clarity. If a Braille word exceeds the available space, it is hyphenated after the first syllable. Other file formats in the EPUB file, such as video or audio files, are not processed as they are not used later for the tactile representation. The final tactile format is then displayed on the 2D tactile display, which is connected through TCP/IP connection.

3.3.1.2 EPUB TUI Design

The implementation of the EPUB interface follows a Model-View-Controller (MVC) architecture [114], as illustrated in Figure 3.7. MVC is a software design pattern that separates an application into three interconnected components: the model, which manages the data and business logic, the view, which handles the presentation layer, and the controller, which processes user input and coordinates interactions between the model and the view. In this implementation, the model component includes classes such as *Document* and *DocumentPage*, which represent the content and structure of EPUB files.

The Controller is responsible for handling user interactions. The *CommandHandler* class processes commands derived from tactile input events, which are collected by the *DisplayInput* class. These events include touch gestures and button presses. The *DisplayConnector* class adapts data into a format suitable for the 2D tactile display. Text-to-speech functionality is supported by multiple engines, including *ESpeakTTS*, *MimicTTS*, and *AlsaTTS*, all of which inherit from the abstract *TextToSpeechConverter* class.

The View component consists of classes that manage how data is presented on the 2D tactile display. Structural and simplified views are rendered by the *OverviewPrinter*, which displays elements as tactile boxes. Content views are managed by *ImagePrinter* and *TextElementPrinter*, both of which inherit from the *BrailleTranslationPrinter* class. This base class is responsible for converting text to Braille and preparing images either as tactile representations or as alternative text. The *BrailleDisplay* class represents the 2D tactile display itself. It manages the pin-matrix buffer and handles operations such as scrolling, screen clearing, and rendering updates. For this purpose, it uses the *ElementPrinterFactory*, which stores all the *ElementPrinter* instances required to represent document elements on the display.

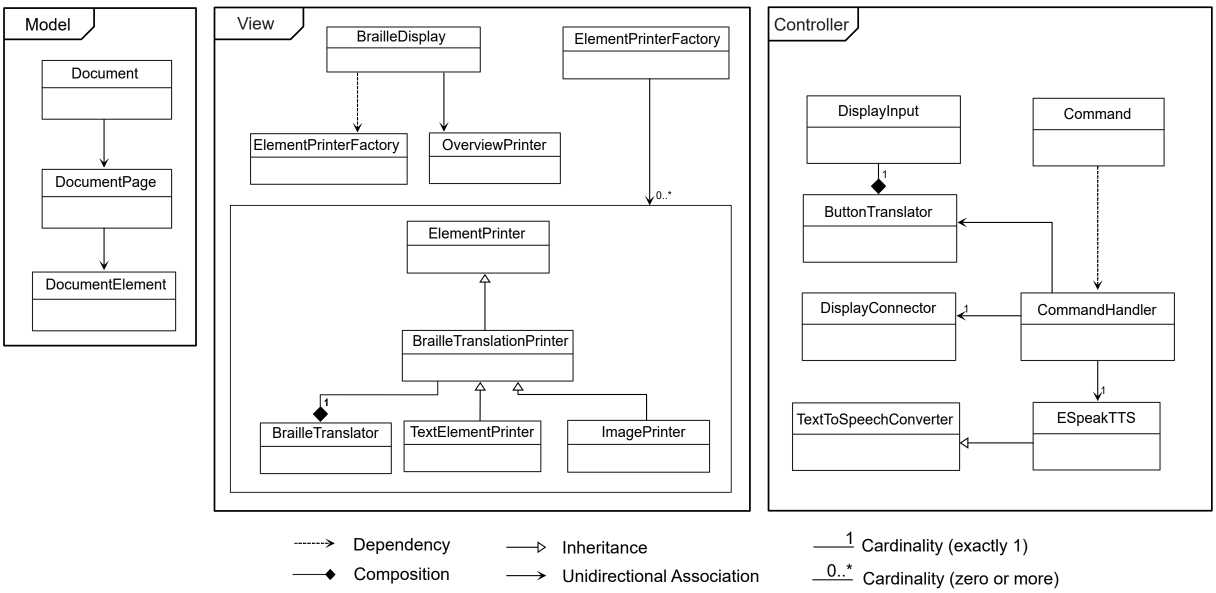


Figure 3.7: Conceptual class diagram of the EPUB TUI, based on MVC architecture.

The interface provides three viewing options for presenting EPUB document pages: structure view, reduced structure view, and content view. The following sections discuss these view modes in detail.

Structure View: The structure view displays bounding boxes corresponding to the elements on the page with the original position and size of each element, as shown in Figure 3.8 (a). An identifying letter of the corresponding XHTML tag is added on the upper left corner, as shown in Figure 3.8 (a) the highlighted corners of the bounding boxes, of each rectangle to identify the type of the element, as shown in Table 3.7, e.g. the Braille letter 'h' represents a header and 'p' represents a paragraph to inform the reader of the type of content.

Element Type	Element Identifier Braille Letter
Header H1- H6 (h)	⠓
Paragraph (p)	⠏
Section (s)	⠎
Image (i)	⠊
Hyperlink (a)	⠁
Equation in LaTeX format (l)	⠇

Table 3.7: Element identifier symbol for each element type in the EPUB document.

Reduced Structure View: The reduced structure mode omits paragraph and section elements, leaving only headings, images, and equations. This mode aims to simplify the search for key elements by removing text elements that occupy significant space. This view mode is based on the recommendations of Bartalesi et al. [86] of toggling the visibility of complex data elements.

Content View: The content view presents all elements in a sequential manner according to their arrangement in the XHTML file. Images are depicted either by their alternative text or if no text is provided, an empty text placeholder is shown to indicate the presence of an image to the user. Each element is accompanied by an indicator letter on its left, similar to the structure view, as depicted in Figure 3.8 (a).

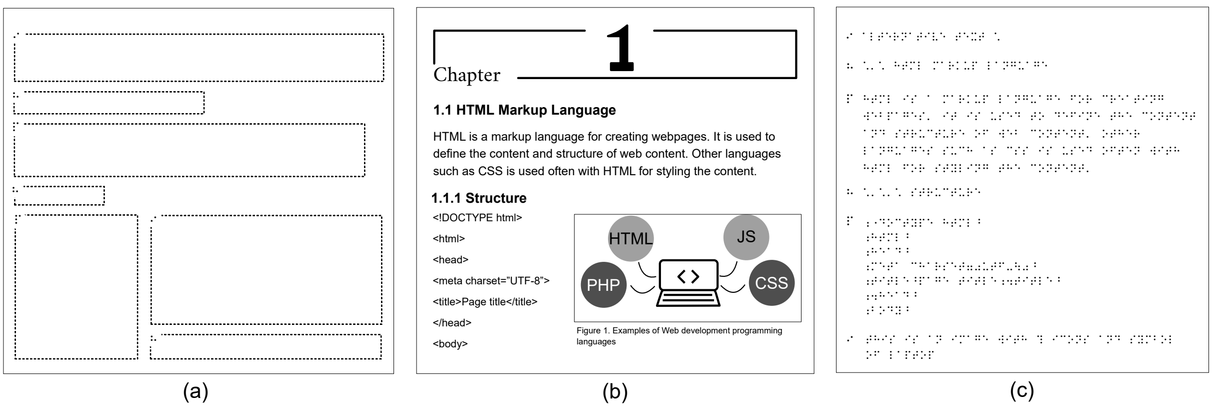


Figure 3.8: Available views in the EPUB reader. Highlighted areas in both views display the Braille letter serving as the element identifier. (a) The structure view, showcasing the layout of the first page of the EPUB document shown in (b). (b) The original format of the first page of an EPUB document. (c) The content view representation of the same page, where all elements are arranged in a linear, stacked format.

3.3.1.3 Interaction Concepts

The interface includes 11 interaction concepts, and the button layout was designed similar to the interactions of the document interface presented in the previous section. The interactions utilize the buttons available in the HyperBraille display and also include touch-based interactions. The interactions, as shown in Figure 3.9, are as follows:

1. **Change Orientation:** Button 1 rotates the current view by 90 degrees.
2. **Scroll Pages:** Buttons 2-right and 2-left enable the user to navigate to the next or previous page, respectively
3. **Element Scrolling:** Buttons 2-up and 2-down scroll by element.
4. **Switch View Mode:** Button 3 enables the user to switch between structure and content view.
5. **Navigation Page:** Button 4 displays the navigation page (table of content). By pressing the same button again, the user can return to the last page that was displayed before moving to the navigation page.
6. **Default Mode:** Button 5 switches to the default mode in the structure view.
7. **Reduced Mode:** Button 6 activates the reduced mode in the structure view, where all text paragraphs are filtered.
8. **Page Information:** Button 7 reads the current page number by the Text-to-Speech Synthesizer (TTS).
9. **Audio Feedback:** Pressing Button 8 in the content view mode triggers audio feedback, reading aloud the displayed text.
10. **Move to Section:** By double tapping inside the boundary box of any paragraph in the structure view, the content of the section is displayed in the content view.
11. **Line Scrolling:** Button 10 scrolls line by line (4 Braille rows at a time).

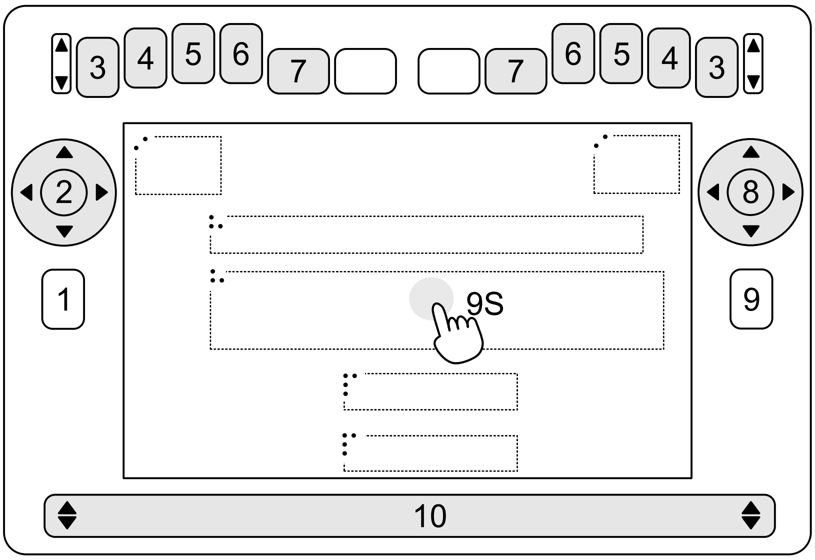


Figure 3.9: Available interactions in the EPUB system on the HyperbBaille display. The Gray color indicates buttons currently in use. 1) Horizontal / vertical orientation switch, 2-right) page forward, 2-left) page backward, 2-up) element scroll upward, 2-down) element scroll downward, 3) structure / content view switch, 4) navigation page, 5) default mode in structure view, 6) reduced mode in structure view, 7) current page and line number, 8) stop TTS, 9) touch enable interaction 10) element scroll.

3.3.2 Evaluation

A preliminary study with two blind users was conducted to evaluate and refine the design of the reader and the interaction concepts. The study had two main objectives: (a) evaluate how easily blind users can read and interact with EPUB documents using 2D tactile displays, and (2) whether the users can easily and quickly search for specific elements using the interface.

3.3.2.1 Participants

Two blind male participants (P1, P2), aged between 50–60 and 20–30, respectively, were recruited via university mailing lists to test the EPUB system and provide their feedback. Both participants had experience with various 2D tactile displays and eBooks in EPUB format, and both were proficient Braille readers.

3.3.2.2 Procedure

Each test lasted one hour and comprised the following three sessions:

- **Session 1 (10 min):** Questions about demographic information, including the participant's age and their experience with both tactile displays and eBooks.
- **Session 2 (20 min):** Introducing the participants to the different view modes and navigation techniques using an example document. During this session, participants navigated a short document, and were tasked with locating a mathematical equation on the second page.
- **Session 3 (30 min):** participants interacted with another EPUB document, and completed two tasks: (1) finding specific information on the currently viewed page, and (2) navigating to specific information in a particular chapter.

All sessions were audio recorded, and notes were taken on participants' comments.

3.3.2.3 Results

Both participants were able to read the document and solve the given tasks. Both used their index finger for selection, and it was observed that using a double-tap for selection could sometimes cause issues, particularly when the user prefers to keep one hand on the text while reading. This was confirmed by the feedback we received from participant P1 who suggested implementing a toggle button for enabling and disabling the touch functionality to prevent inadvertent clicks during screen exploration. Alternatively, the participant proposed a method for executing touch functions by placing a finger on an element and simultaneously pressing a touch button. Additionally, it was noticed that the participant often needed to interrupt the audio feedback after listening to the first few sentences. Moreover, the user reported confusion caused by closely placed boxes in the structure view, especially when the distance between them is one pin or less. They recommended specifying a minimum fixed distance between the boxes to resolve this issue.

P2 shared his impressions of the new presentation format for EPUB documents, stating:
"That is really interesting because I have never had, for example, multi-column format under my fingers, because as a blind person, everything is always displayed vertically."

The participant also reported a preference for the structure view over the other two view modes and he answered when asked about the reason for this:
"I found it great that you have a bit of an overview of what the document really looks like."

Regarding the reduced structure view, P2 mentioned that this view mode was not intuitive for him. The participant commented that this view no longer corresponded to the original structure of the document which he identified mentally using the structure view mode. Compared to P1, he did not use the reduced structure view mode during the test.

The element identifier was shown to help distinguish between various elements in the document, however, it was observed that closely situated elements sharing the same identifier could occasionally lead to confusion. This occurred when one of the elements was pressed, and it became challenging to discern which specific element was clicked on, especially when displayed in content mode. To address this issue, the P2 recommended appending numbers to element identifiers to differentiate closely positioned elements sharing the same identifier. For example, if three paragraphs are aligned on the same line, their identifiers should be designated as p1, p2, and p3. Alternatively, the participant also proposed incorporating an option to audibly access either the content or the summary of an element without the need to switch to content view mode.

3.3.2.4 Discussion

Both participants in the preliminary study were able to read an EPUB document and navigate to the different chapters and search certain elements within it. However, regarding the different views in the EPUB reader, it was noticed that the structure view and content view were the most frequently used modes during the tests. In contrast, the reduced mode was not used by the first participant, while the second participant found it unclear and unnecessary to locate specific information within the document. This may be attributed to the altered document structure in the reduced mode, which differs from the familiar behavior of reading documents on computers or mobile phones. However, it would be valuable to analyze whether offering the reduced mode in the content view would benefit users. Additionally, it was important to define a minimum distance between the different bounding boxes in the structure view to avoid confusing closely placed elements.

Regarding searching for certain information, it was noticed that one participant was faster using the content view in comparison to using the structure view. One reason for this can be that in the content view, it is possible to scroll by element. This has the advantage that large elements can be quickly skipped, which in comparison to the structure view, would require more scrolling. Another explanation for this is, as the participant mentioned, is due to the following advantage in the content view: by simply locating their finger on the element symbol of the first element and scrolling element by element, the element symbol of the next element appears in the exact same position, which was helpful for the participant to quickly locate the element with the symbol he was looking for. The reduced mode's limited adoption highlights the influence of familiarity on users' preferences. Representing data in formats that deviate significantly from common paradigms may require additional training or redesign to align with blind users' expectations.

Regarding the implemented interaction concepts, the observations during the preliminary study underscored the importance of maintaining an overview of the content during interaction. For example, users appreciated the ability to listen to audio feedback for a specific element while simultaneously keeping one hand on the tactile text. This highlights that multimodal interaction concepts that combine audio feedback with concurrent Braille translation are important for user interfaces that run on 2D refreshable tactile displays. These findings align with those of Prescher et al. [115], who emphasized that interaction concepts for 2D refreshable tactile displays must prioritize minimizing disorientation and maintaining constant tactile engagement with the data.

Some additional interactions were suggested by the participants. For example, they recommended the ability to access a summary of an element by placing a finger on it and pressing a specific button, which would trigger an audio summary without requiring a switch to the content view. The need for a toggle to stop the audio feedback at any point, as requested by one of the participants, further emphasizes this desire for a summary feature, as users may want to listen to only a portion of the text to quickly gather the key information. However, further analysis would be required to explore this. Additionally, one participant expressed interest in the ability to edit the document and add comments while reading, which was also a common request in the survey by Leporini et al. [87].

Both participants found the navigation page option highly useful, though they utilized it differently. The first participant used it primarily for reading, switching between chapters as needed, while the second participant relied on it mainly to locate specific information. For this participant, the ability to quickly navigate between chapters was particularly advantageous. This aligns with the findings of Bartalesi et al. [86], where survey participants emphasized the need for a quick navigation structure, such as a table of contents, to efficiently jump to specific sections.

3.3.2.5 Limitations

While the preliminary study provided valuable insights into the usability of different views and interaction concepts for 2D tactile displays, some limitations must be acknowledged. Broader testing with a more diverse group of users, including those with varying levels of familiarity with EPUB documents and tactile displays, would provide a more comprehensive understanding of user preferences and challenges. Additionally, the preliminary study focused on qualitative data concerning user preferences and usability issues. While these insights are valuable, future research would benefit from incorporating objective performance metrics, such as reading speed, task completion time, and error rates, to provide a more comprehensive and quantifiable evaluation of the system's effectiveness and interaction modes. Furthermore, to establish the relative advantages of the proposed TUI, it is essential to conduct comparative studies against existing assistive technologies, such as screen readers, commonly used by individuals who are BLV to access EPUB documents. Such comparisons would help validate the practical benefits and potential improvements offered by the 2D tactile display approach in this context.

Future research could also explore how the system could be adapted to other 2D tactile displays with different resolutions or interaction capabilities. Understanding how the system performs across various display technologies would enhance its broader applicability. Additionally, investigating how to accommodate both Braille and non-Braille readers, possibly through alternative interaction concepts or adjustable modes tailored to varying literacy levels, would be valuable in expanding the system's usability.

3.3.2.6 Improvements to the TUI Design

Based on the feedback provided by participants, four modifications were made to improve the interactions available in the interface:

1. **Touch Enable Button:** In response to P1's suggestion, a touch enable button (Figure 3.9, Button 9). This allows the user to interact with any document element by simultaneously placing a finger on the element and pressing the touch button to avoid inadvertent clicks.

2. **Interrupting Audio Feedback:** To address usability concerns, an option was introduced to interrupt the audio feedback. Users can now toggle the audio button (Figure 3.9, Button 8) at any time to stop or start the audio feedback anytime, enhancing control over auditory interactions.

3. **Enhanced Audio Functionality:** Following P2's recommendation, the audio feedback feature was modified to provide immediate access to content when users place a finger on an element identifier in the structure view and listen to the corresponding content without needing to switch to the content view mode.

4. **Improved View Mode Differentiation:** Adjustments were made to the spacing between adjacent bounding boxes in the view modes to improve tactile differentiation. A minimum gap of 2 pins was added between all elements displayed, ensuring clearer boundaries between boxes.

3.4 Tactile Graphics System for 2D Tactile Displays

This chapter discusses how 2D tactile displays can be used to provide access to complex graphics, such as charts, diagrams, and technical illustrations in a tactile format for users who are BLV. It focuses specifically on vector-based graphics and how they can be made accessible through such displays.

One key feature of vector graphics is that they represent drawings using mathematical equations. This allows graphics to be displayed independently of the screen resolution. As a result, even tactile displays with small amount of pin-matrix can support detailed exploration by allowing users to zoom into specific areas. SVG format was chosen as the primary format due to several technical and practical advantages, which were discussed in Section 3.1.3. The section introduces a tactile graphics system for parsing and rendering SVG images, and presents the findings from a user study with five blind participants.

The main contributions of this section are:

1. A graphics system that handles the pipeline of parsing SVG, scan conversion and rendering of geometrical shapes into a tactile format.
2. Interaction concepts that enable the users to interact with vector-based graphics through touch, buttons, and audio.
3. Findings from a user study with five blind participants to assess the effectiveness of the interface in conveying technical diagrams, such as UML diagrams.

This section is based on a publication in Haptic Symposium 2024 [1]. Some texts remain unchanged from the original publication.

3.4.1 Overview of the System

The tactile graphical system utilizes the SVGT 1.1 specification for vector-based graphics. This choice reflects considerations for future mobile-integrated tactile devices, which may face constraints such as limited memory and processing power. Moreover, many of the extended features introduced in SVG Tiny 1.2, such as color transparency or visual filters are not applicable to tactile displays. These displays operate in a binary mode, with each pin or pixel having only two possible states: raised (on) or flat (off). As a result, simple geometric shapes and basic structural information are sufficient for effective tactile representation. Supporting SVGT 1.1 ensures a lightweight yet expressive format that aligns well with the functional and technical constraints of tactile output.

The tactile graphics system includes two main components: a parser for the XML input file and a graphics pipeline responsible for transforming vector-based image descriptions into a format suitable for tactile rendering. The XML parser extracts geometric and stylistic information from the input file, such as shape types, coordinates, line widths, and fill properties. This structured information serves as the input for the rendering pipeline.

The graphics pipeline performs the necessary scan conversion to convert the geometrical shapes into a discrete grid representation that matches the resolution of the 2D tactile display. The pipeline accounts for the physical resolution and constraints of the tactile surface by scaling the image to fit on the available pin-matrix size.

3.4.1.1 SVG Graphics TUI Design

The TUI implements both touch- and button-based interaction concepts that enable the user to perform necessary operations such as zooming, panning, and accessing textual information. Users can explore diagrams in SVG format in tactile representation using haptic interactions, buttons, and audio feedback. The interface was implemented to run on the HyperBraille display [69].

Figure 3.10 shows a simplified UML class diagram of the interface. The *AppController* class serves as the central coordinating component of the system. It manages the creation of the *SvgViewer* and *SvgModel* classes, which are responsible for the rasterization and depiction of geometrical objects in tactile form, and for parsing and extracting structural information from SVG files, respectively.

Computational tasks, such as performing geometric transformations and scan conversion, are handled by the *MathUtilities* class. It implements rasterization algorithms, including Bresenham's line algorithm and the midpoint circle algorithm [116], to convert vector-based shapes into rasterized formats. These rasterized objects are then passed to the *Renderer* class, which is responsible for rendering them on the tactile display. Finally, device-specific constraints and settings are managed by the *DisplayConfigurator*, enabling the interface to adapt to various tactile display configurations.

The *WindowViewer* defines an interface for rendering content on the tactile display. It supports viewport adjustment and manages user interactions within the display area. The *TextLayout* and *BrailleTranslator* classes handle the translation of text into Braille and the formatting of text to ensure it fits the screen appropriately. This includes avoiding word breaks across multiple lines, thereby improving accessibility.

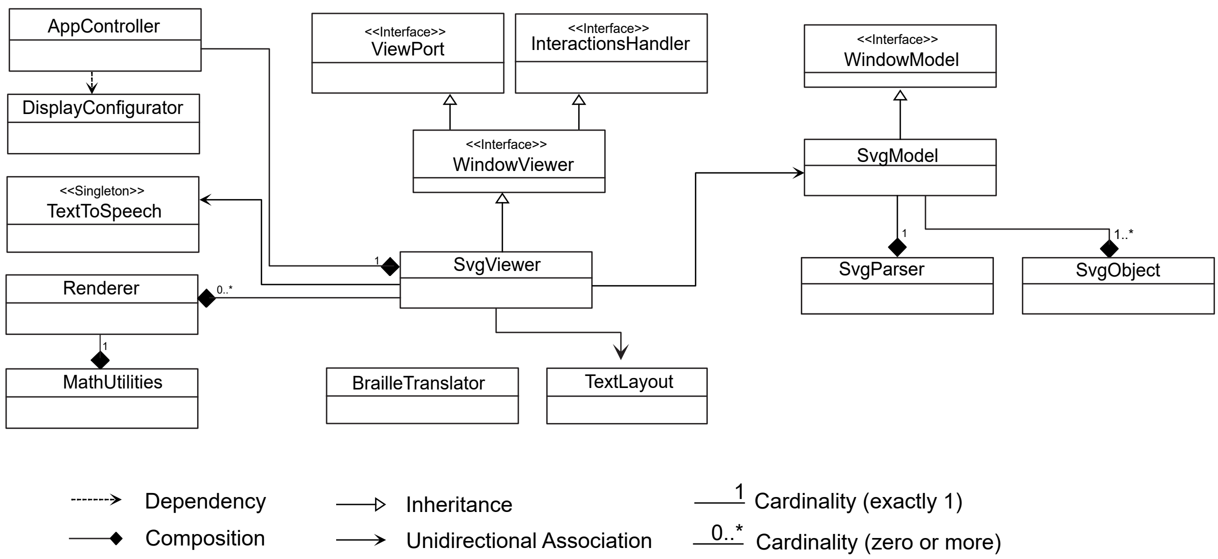


Figure 3.10: Simplified class diagram for the architecture of the graphics TUI.

During the design phase, a blind user was consulted to ensure the interface meets the needs and preferences of the end users. One of the features requested by the user was the ability to navigate using both hands. To address this need, the same interactions were implemented using the right and left keys in the HyperBraille display, enabling the users to easily navigate using one hand while keeping the other hand always in contact with the diagram. Additionally, the user strongly preferred having the text translated into Braille rather than relying solely on audio feedback. The following section provides a comprehensive discussion of our interface design.

Following the approach of Loitsch et al. [117] of using a cross symbol to represent lengthy text elements, our interface adapts a similar strategy. In the initial view, the diagram is scaled to suit the dimensions of the tactile display. Within this view, all text elements are substituted with the Braille letter 'T', positioned at the center of the respective text, as depicted in Figure 3.11 (a). This approach serves to simplify the diagram's details, enabling the user to scan the diagram.

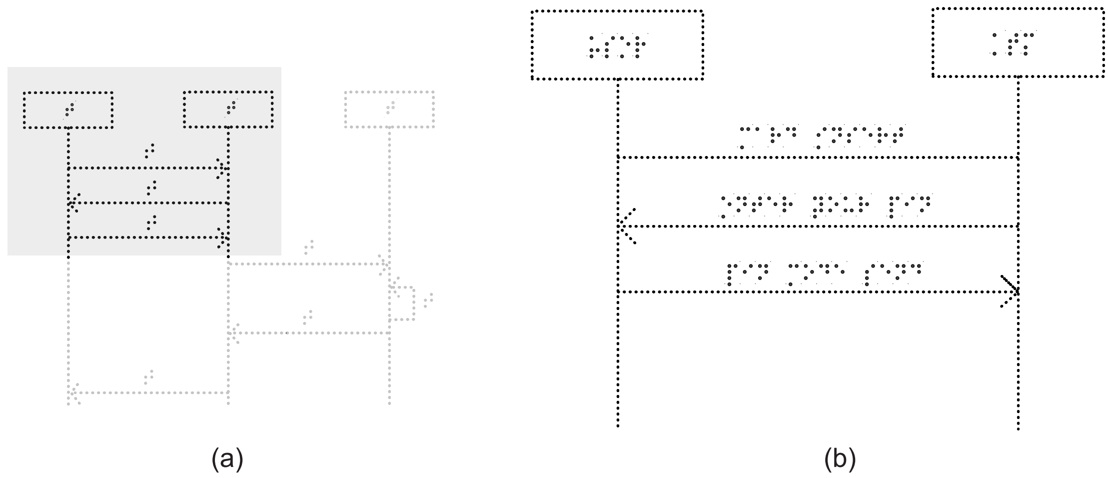


Figure 3.11: Tactile representation of a sequence diagram in different view modes. (a) Original view with reduced complexity by substituting text with Braille letter T. (b) Enlarged view of the grey area shown in (a), with full text in Braille.

3.4.1.2 Interaction Concepts

The interface incorporates a combination of touch-based and button interactions that enable blind people to explore diagrams on 2D tactile displays. The first interaction in the interface is the touch selection. Users can employ a single finger to indicate a specific text element in the diagram. They can receive an audio description of the selected text element by simultaneously pressing the audio button, depicted in Figure 3.12 (2). Furthermore, the interface includes zooming and panning functionalities. Users can achieve zooming by scrolling the zoom button, illustrated in Figure 3.12 (1), either upwards or downwards, enabling them to magnify or reduce the focus on the central area of the diagram. Additionally, they can explore the zoomed-in diagram by moving it with constant step size using the cursor buttons, shown in Figure 3.12 (F).

As the user zooms into the diagram, reaching its original size, the actual text is presented in Braille, as shown in Figure 3.11 (b). This strategy ensures that blind people can easily switch between the overview and the details of the diagram without feeling overwhelmed by excessive information. An additional interaction option is the "fit on screen" button, as shown in Figure 3.12 (F), which allows the user to switch to the initial view from the zoomed-in mode at any time.

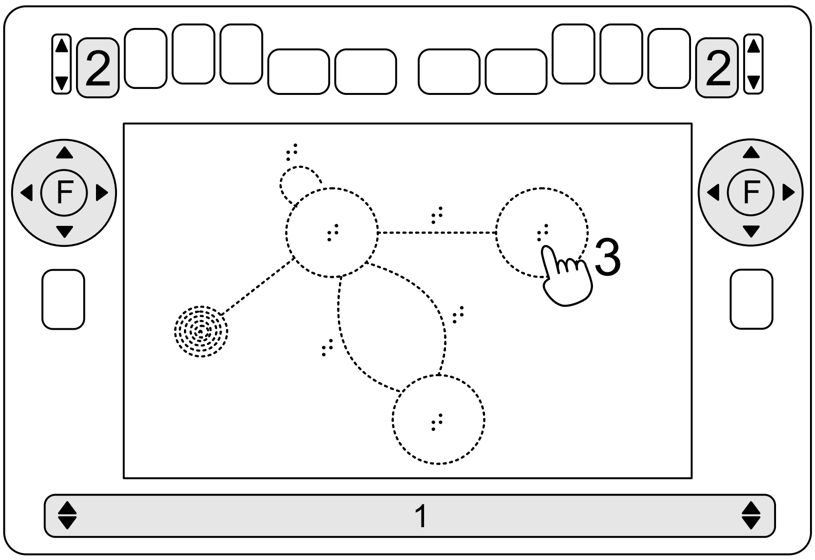


Figure 3.12: Interaction buttons on the HyperBraille display. (1) Zoom, (2) audio, (3) summary, (4) touch, (P) navigation Buttons, (F) fit on screen.

3.4.2 Evaluation

To evaluate the usability of the proposed interface, a user study with five blind participants was conducted. The study has been approved by the ethics committee at Karlsruhe Institute of Technology. The study focused on the following three objectives: (a) measuring the effectiveness by determining how successful the users are in using the interface for exploring technical diagrams, (b) assessing the efficiency by measuring the time and effort required to complete the given tasks, (c) analyzing how satisfied the users are with the interface and its interactions, and if they prefer it over their currently used methods.

For the assessment, for types of UML diagrams were used, as shown in Figure 3.13. UML language has been widely used in education [118, 119] and as a modelling standard in industry [120, 121]. UML diagrams heavily rely on graphical notations to convey the relationships among the various elements within the diagrams, which can be particularly challenging for BVI users [122]. It is noteworthy to mention that all the participants in the study were either pursuing computer science education or employed in roles related to software systems, therefore, they were expected to be familiar with such diagrams.

3.4.2.1 Participants

Five participants (1 female and 4 male) were recruited via campus email lists. The participants' age ranged from 24 to 54 years, as shown in Table 3.8. All participants had a high level of education of at least a Bachelor's degree or higher and they can read Braille. In the context of accessing technical diagrams, participants employ different methods. Two participants (P3, P5) use screen readers for auditory descriptions, one (P1) relies on a sighted user's explanations, and the rest (P2, P4) utilize embossed representations. Four participants (P2, P3, P4, P5) had prior experience with or were familiar with 2D refreshable tactile displays. They have previously tested an interface for depicting PDF files on the HyperBraille display.

ID	Age Range	Gender	Vision	Used Method
P1	18–27	Female	Blind	Description from sighted person
P2	18–27	Male	Blind	Embossed tactile diagrams
P3	18–27	Male	Blind	Textual description
P4	48–57	Male	Blind	Embossed tactile diagrams
P5	18–27	Male	Blind	Textual description

Table 3.8: Participants demographic information and preferred method for accessing UML diagrams

3.4.2.2 Procedure

The user study began by providing each participant with a demo flow diagram, shown in Figure 3.13 (c), and a step-by-step instructions for 15 minutes, guiding them on how to use the interface on the HyperBraille tactile display to explore the diagram. Following the demo phase, the participants were given three UML diagrams: a state machine, sequence diagram and a class diagram, as shown in 3.13 (a)(b)(d), and were asked to explore each diagram in five minutes. Afterwards, they were given the following tasks to perform:

- **Task 1**: Layout: in this task, the participant is asked to explain the existing elements in the diagram. This task provides insights into the participant's knowledge of the diagram's layout.

- **Task 2**: Readability: the participant is asked to explain the topic in the diagram. This task shows the participant's ability to interpret and explain the information and relations presented in the diagram.
- **Task 3**: Orientation: if they can point to specific information in the diagram. This task aims to evaluate whether the interactions provided can assist users in navigating and retrieving the desired details from the diagram.

After finishing the tasks, there was a final phase of open-ended questions to rate the overall experience with the interface. In this session, the participants were asked for their suggestions and if they noticed any limitations in the interface. Additionally, the participants were asked to answer the standard ten questions in the system usability scale (SUS) questionnaire to assess their overall satisfaction on a 5-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree).

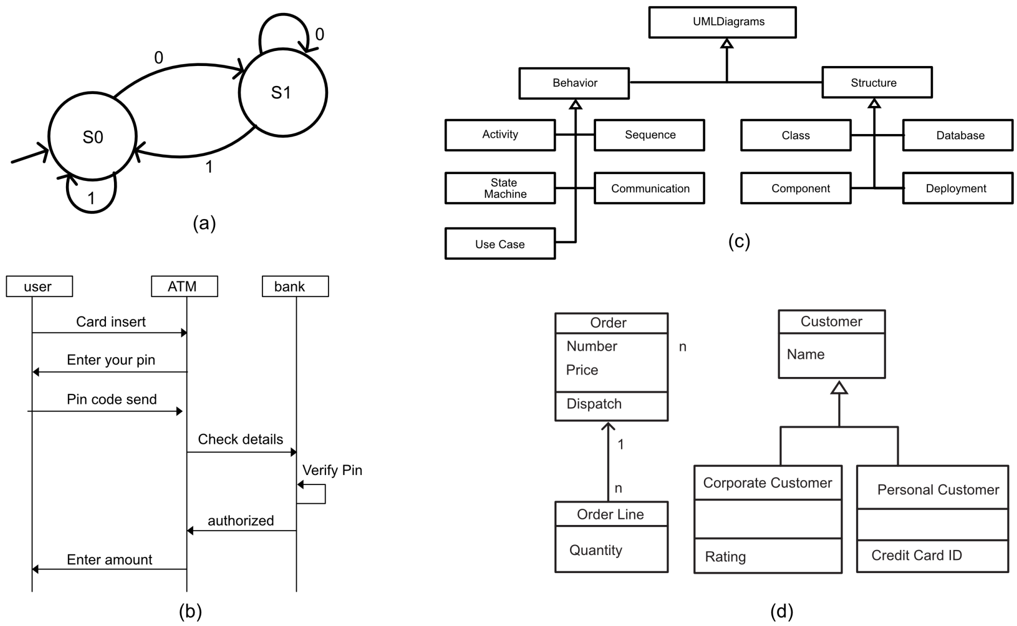


Figure 3.13: Different types of diagrams used during the user study: (a) state diagram with two states, (b) sequence diagram of an ATM process, (c) flow diagram describing the different types of UML diagrams, (d) class diagram of corporate customer types

3.4.2.3 Results

The average success rates for the three tasks were as follows: 90% for the first, 80% for the second, and 85% for the third. Regarding the user satisfaction questionnaire, the SUS score was calculated to be 86.5%. Overall, the participants strongly agreed that they were able to grasp the layout structure of the diagrams using the available interactions. All the participants described themselves as very successful in completing the tasks. Moreover, the feedback from the participants indicated satisfaction with the available interaction methods and the approach of hiding the complete text when showing the diagram in the original size. Several participants (P2,P4,P5) expressed interest in the potential of the interface to depict other types of diagrams, such as electrical circuits and chemical structure diagrams.

3.4.2.4 Discussion

Overall, it was noticed that there was great appreciation from all the participants for the possibility of being independent when working with diagrams and being able to explore them without needing the help of a sighted person. P2, for example, could count and describe all the shapes in the state machine. It was noticed that the sequence diagram was the most comprehended (three out of five participants). P2 mentioned that the sequence diagram was his favorite diagram in the tasks, and when asked about the reason, the participant replied:

It was easier to follow the structure of the diagram, as the positions of the lifelines were well defined, so I was able to build a mental image in my brain

P1 answered when asked if she prefers this interface over the method she currently uses: *Definitely, yes, this is much better than getting the description from someone else. This gives me more confidence.*

Participants P3 and P5 also expressed a preference for having access to the original diagram rather than relying solely on a textual description of it. Furthermore, both P3 and P5 mentioned that they would prefer a 2D tactile display over embossed papers if given the option. They considered a tactile display more practical and beneficial in exploring and interacting with graphical diagrams.

Two of the participants who had experience with the HyperBraille (P4 and P5) mentioned that compared to another interface they had previously tested, they were happy about the possibility of accessing text in Braille.

3.4.2.5 Limitations

Two participants (P4 ad P5) provided feedback indicating occasional difficulties in understanding and exploring the diagrams. They expressed the need for a clear exploration strategy, such as receiving an indication of a starting point for exploring the diagrams.

Additionally, some limitations were noted in the overview mode, where the diagram is adjusted to fit the screen. In this mode, the positioning of Braille text occasionally intersects with the edges of geometric shapes, which is confusing. A potential solution is introducing a defined spacing or margin between the Braille text and the graphical elements to enhance clarity. Another observation was that using various shapes for the arrowheads in the diagrams led to confusion for two participants (P2 and P3). As a solution, these participants recommended implementing touch or audio feedback to indicate the distinctions between arrowhead shapes.

3.5 Conclusions

This chapter explored the design and implementation of three TUIs aimed at supporting individuals who are BLV in accessing common digital content formats used in STEM fields, through the use of 2D refreshable tactile displays. Each interface targeted a specific content type: documents in PDF, eBooks in EPUB format, and technical diagrams in SVG format. The interfaces were developed by combining insights from existing TUIs in the literature with a user-centered approach involving collaboration with a blind user throughout the design process.

The first interface introduced a method for presenting the spatial structure of PDF documents, utilizing a document layout analysis approach based on the YOLOv10 detection model to extract complex layouts and metadata from inaccessible PDF files. The second interface extended this work to EPUB documents, offering multiple view modes and supporting navigation across sections and chapters. This interface was developed closely with blind users, who emphasized the usefulness of structure and content views for locating relevant information. The third interface addressed the challenge of representing technical diagrams in SVG format. Through zoom, pan, and audio features, it enabled participants to explore intricate visuals and access textual labels independently.

Participants notably appreciated the ability to access documents and graphics in their original 2D spatial format, rather than relying solely on alternative text descriptions. This access provided a richer and more intuitive understanding of content layout and visual relationships, which alternative text alone often fails to convey. Additionally, the participants mentioned that having access to the original document structure allowed them to “feel” how the documents truly look and experience their authentic organization, which they found especially useful for comprehension and navigation. These findings challenge the common misconception that blind users only require alternative text for graphical content and audio-based access to documents, emphasizing instead the importance of tactile and multimodal representations for more complete and meaningful access.

Across all three systems, participants consistently reported improved understanding of the structure and content of materials, alongside a stronger sense of independence. These results highlight the potential of 2D tactile displays as platforms for multimodal content exploration. Moreover, the approach of leveraging existing guidelines such as WCAG and visualization principles like Schneiderman’s VISM, combined with continuous consultation with blind users, proved successful in creating accessible and usable TUIs for 2D refreshable tactile displays.

4 Designing a Low-Fidelity Prototyping Method for Co-Designing 2D Tactile Displays

This chapter analyses how assistive technologies can be co-designed with individuals who are BLV. It begins with a brief review of prior work on co-design principles and prototyping approaches that enable individuals who are BLV to participate in design workshops.

In this context, the goal of this chapter is to provide an inclusive prototyping method that enables participants who are BLV to actively contribute to the development of assistive technologies, thus providing answers to the following research questions:

> **RQ1:** How can lo-fi prototyping methods be adapted to effectively involve individuals who are BLV in the design of accessible technologies?
>
> **RQ2:** How to structure prototyping workshops to prioritize individuals who are BLV, and what roles should sighted assistants play?

In order to answer these questions, a new methodology is presented which is structured in two phases: in the first phase, four exploratory workshops involving one blind participant were conducted, to iteratively develop an adapted lo-fi prototyping approach and a toolkit that would enable the target group to design their own prototypes of 2D tactile displays. The resulting haptic toolkit includes 3D printed buttons and control elements, a magnetic box representing the device's case, a printed list in Braille with the basic features of the device, and "tactile screenshots" of tactile software UIs. The toolkit realizes the principles of lo-fi prototyping by being cost-effective to produce and providing a simple way to allow end users to provide feedback and ideas on usability and functionality before more resources are committed to detailed design and development.

In the second phase, the resulting toolkit and workshop structure were applied in six prototyping workshops involving 12 blind participants. The results of these workshops showed that the prototyping approach and the toolkit enabled the participants to design and discuss their ideas and preferences. Furthermore, it encouraged creative input from the users regarding new features that should be considered in future 2D tactile displays.

Through this chapter, the following two main contributions are made:

1. An adapted lo-fi prototyping method and toolkit specifically designed by and for participants who are BLV, allowing for rapid prototyping of 2D tactile displays.
2. Set of recommendations for structuring lo-fi prototyping workshops to enhance creative input from users who are BLV, while also reflecting on the role of sighted assistants in such workshops.

This chapter is based on a publication in ACM SIGACCESS Conference on Computers and Accessibility (ASSETS) 2025 [4]. Some texts remain unchanged from the original publication.

4.1 Context

Involving people who are BLV in the design process of assistive technologies is essential for understanding their needs. Panne et al. [123] highlighted that a frequent cause of innovation failure is the disconnect between how end-users interact with systems and how designers envision these interactions. This issue is particularly evident in assistive technology design, where the absence of user involvement often results in devices being abandoned for failing to meet users' needs [124, 125].

To address this challenge, various co-design approaches have been proposed in the literature to involve end-users actively in the design process, positioning them as co-creators rather than subjects of research [126, 127, 128]. One method that supports such involvement is design workshops, which can facilitate active participation. A common approach employed in design workshops is lo-fi prototyping [129, 130]. Lo-fi prototyping involves using simple, often hand-drawn, or basic digital tools for the generation of ideas and rapid testing of concepts. While this approach facilitates early-stage feedback [131], it relies heavily on visual elements, such as sketches and storyboards [132]. This reliance poses significant challenges for people who are BLV, hindering their participation in the early stages of design [133].

To overcome these barriers, several studies have explored how lo-fi prototyping processes can be adapted for blind and low vision users by incorporating alternative materials, such as cardboard mock-ups, rubber bands, Lego models, or tactile paper [134, 135, 136]. This adaptation is important to involve users who are BLV in designing assistive technologies that align with their needs and preferences. In this section, a review of existing research on design methods that involve people who are BLV is presented, focusing on the strategies and challenges associated with their engagement in the design process. Additionally prior work on designing 2D tactile displays is examined.

4.1.1 Design Methods Involving People Who are Blind or Have Low Vision

Various methods are described in the literature that involve users who are BLV in the design process by offering alternatives to the visual nature of traditional design methods.

Sahib et al. [137] proposed a participatory approach based on textual narrative scenarios for designing a web search interface with blind users. The approach depends on including one blind user as a full member of the design team to develop the scenario which would be later used in prototyping sessions. As the researchers discussed such textual methods can be beneficial for gathering ideas, however, it was necessary to describe any artifacts that are part of the scenario in significant detail. One limitation of this approach, as noted by the authors, is the dependency on one person in the early exploratory stages, which limits the diversity of preferences while creating the scenarios. Similarly, in a study by Okamoto [138], a scenario-based approach was employed to facilitate rapid communication between designers and blind users during workshop activities for designing new devices. However, the method was not described in detail.

Some approaches proposed the use of haptic materials for evaluating software interfaces. For example, Miao et al. [134] presented guidelines for evaluating the concept and layout of a software UI. For this, they used embossed papers to represent the layout and concept of the UI. The researchers mentioned that it is essential to map geometrical shapes as precisely as possible while maintaining the proportions and scale of the original output device. Additionally, it was important to proofread all the mock-ups used in the studies by someone who is blind before running the tests. Additionally, they advise seeking guidance from blind experts to prepare suitable explanations in advance.

Ramloll et al. [135], in their work on designing haptic line graphs, employed a participatory approach with blind students to create lo-fi prototypes. Participants used pins and rubber bands to construct line graphs on soft wooden boards. However, this method required constant assistance from sighted teachers because blind participants needed both hands: one to hold the drawing and the other to press the pins, posing a risk of injury.

Similarly, Elmqvist [136] research on visualizations for blind individuals explored the translation of visual information into tactile formats, employing materials and techniques that enable users to interact with data representations. His approach involved using a metal board, magnets, and ice cream sticks to recreate visualizations for a blind student. However, this method has not yet been formally evaluated with a larger group of blind users to determine its overall effectiveness.

4.1.2 Structuring Accessible Workshops

Some studies in the literature provide insights on structuring workshops to involve people who are BLV and how roles can be defined within these workshops. An example of this is the work of Metalta et al. [139]. In this work, they provided an approach for creating an accessible design process with visually impaired people. They structured their method as a two-stage process. The first stage is an exploratory workshop to identify the challenges and define the best accessible technologies to be used for designing in the second stage workshops. During the first stage, the participants were involved in designing audio-haptic physical lo-fi mock-ups using accessible materials, such as foam paper and electronic tag readers. The output mock-ups of the first stage were converted into highly malleable digital mock-ups that were used in the next stage. In the second stage, a series of prototyping workshops were conducted for a duration of two weeks with the same participants. Visually impaired participants were provided audio diaries to share their thoughts later with the whole team before the next workshops. Challenges noticed with this approach are that creating the lo-fi audio-haptic mockups during the workshop had a negative effect by hindering the participants from expressing their thoughts and communicating effectively.

Another workshop organized at the NordiCHI conference by Magnusson [140] included suggestions for lo-fi haptic prototyping with blind or visually impaired people. One method, proposed by Magnusson et al. [141], introduced an approach of using a combination of LEGO models and scenarios to describe gaming environments. Their suggestions for such workshops stressed the importance of incorporating good scenarios into the prototyping experience to enhance user engagement and provide valuable feedback. Noting that participants may struggle to generate innovative ideas when they cannot envision the application's use in their contexts.

Brewer [142] discussed challenges when conducting co-design sessions with visually impaired participants by utilizing voice- and tactile-based design approaches: Participants in the session encountered difficulties in collaboratively building and refining tactile artifacts, which often led to individual ownership of designs instead of group creations. The researcher suggested that iterative sharing between the participants and clearly defining the roles could enhance shared group representation of tangible designs and ensure that all ideas are adequately considered.

While the involvement of blind users is crucial for creating effective and user-friendly assistive technologies, there remains a significant gap in the literature regarding instances where blind participants participate in the early design stages. Most existing studies focus on the evaluation of given designs rather than enabling blind individuals to take the lead in the design and prototyping stages. In the next section, a new approach for enabling blind individuals to design lo-fi prototypes in design workshops is presented. The approach depends on involving users who are BLV in an iterative process to adapt the materials needed for lo-fi prototyping, and achieve a structure of the prototyping workshops that enables creative input from the users to design their own devices.

4.2 Adapting Low Fidelity Prototyping to the Requirements of Blind Users for the Development of a New 2D Tactile Display

This section outlines the research methodology for developing and evaluating a new lo-fi prototyping approach tailored to users who are BLV. With the focus of designing the hardware of a new 2D tactile display that allows for dynamic exploration of digital information used in STEM fields.

4.2.1 Development of an Initial Low Fidelity Prototyping Toolkit

The first step in this approach depends on defining the key features of the new 2D tactile display that will be created. This includes specifying the hardware input elements such as the device buttons and ports. In addition, the software features should be also specified. This step is essential to create an initial haptic toolkit that allows users to create prototypes of the new device. The toolkit should be intuitive and user-friendly to provide a base that can be further refined later in the process, according to the user feedback.

4.2.1.1 Definition of Initial Features of the New Device

To facilitate the participants' understanding, a set of basic features was defined to help the participants imagine how a 2D tactile display can be used in a realistic context. The features were based on an analysis of currently available 2D tactile displays, as shown in section 2.6.3.1, as well as one of the TUIs presented in chapter 3, namely, the SVG TUI. The two main features were that the display should be able to run 2D tactile TUI and include sufficient device controls and buttons to enable the users to interact with these UIs.

Device Controls and Key Features: The analysis of four existing 2D tactile display technologies provided by the producers, including Monarch, Maetec, Dotpad and Graphiti, served to identify several input and control methods, leading to the definition of the following initial set of basic functions and features:

1. **Home button:** Quickly returns the user to the main menu.
2. **Settings button:** Allows to adjust device settings, such as the device language and Braille settings.
3. **Back button:** Returns the user to the previous screen or action.
4. **Power button:** Turns the device on or off.
5. **Audio button:** Activates or deactivates audio feedback.
6. **Volume buttons:** Controls the audio levels of the device.
7. **Touch button:** Toggles the touch functionality of the display.
8. **USB and HDMI ports:** Provide connectivity options and charging capabilities.
9. **Braille keyboard:** Allows for input using Braille.

Software Tactile UIs: Regarding the software that would run on the new device, two TUIs were chosen. The first interface is the SVG TUI shown in chapter 3.4 for displaying graphical information. The second interface is a file explorer that should allow the user to interact with various files available on the device in as tactile icons on 2D tactile displays. It allows users to select files and navigate through folders and is conceptually similar to the home-screen on iOS devices, which is familiar to many blind and low vision users [143, 144].

The SVG TUI for displaying graphics, such as diagrams and line graphs in a tactile format includes interactions, such as zooming and panning. The zooming concept is implemented by placing a finger on the graph and using designated zoom buttons to make the graph bigger or smaller. Panning is implemented through navigation buttons, allowing users to move the zoomed view of the graphic data. These concepts were already demonstrated and evaluated in section 3.4.1.2.

4.2.1.2 Initial Prototyping Toolkit

The initial toolkit developed consisted of three main components: the UI elements, and a magnetic flat board used to place the UI element on it, shown in Figure 4.1 (a) and (b) respectively, and a textual description of the software UIs. The first component, shown in Figure 4.1 (a), is a 43x30 cm flat magnetic board with various elements that could be used to represent the buttons and control elements of 2D tactile displays. The elements are in various shapes, including rectangles, squares, ovals, and circles, common shapes found in most 2D tactile displays. In addition, the materials selected were commonly used in similar workshops for participants who are blind or have low vision, such as plastic, foam, and wood, to evaluate which materials the participants preferred and which were best suited for building prototypes. Each element was equipped with a five mm diameter magnet, one mm in height, allowing them to be attached to the magnetic board. Additionally, foam rectangle-shaped elements were included in the toolkit to be used as the tactile area or the pins of a 2D tactile display. Additionally, magnetic strips with different lengths were added, to allow the users to separate areas or use them for other purposes. Participants were also provided with clay to model and create arbitrary elements based on their preferences, along with 3D-printed shapes that could be used as cutters to shape the clay if desired.

The second component of the toolkit, shown in Figure 4.1 (b), was another 30x21cm flat magnetic board that functions as the physical case of a 2D tactile display, allowing participants to place buttons and control elements on it.

The third component is a textual description of the two previously discussed software UIs and device controls that explains the available software and interaction concepts, to be read by the session moderator, as follows :

"... the new portable 2D refreshable tactile display featuring two example applications: a file explorer and a graphics viewer. The file explorer will present available files and folders as tactile symbols or icons arranged in a grid structure, while the graphics viewer will allow users to interact with visual data, including zooming and panning."

4.2.2 Co-Design Workshops to Adapt the Toolkit and the Low Fidelity Prototyping Workshop Procedure

In this step, four design workshops were conducted with blind participants, aiming to : (1) refine the initial lo-fi prototyping toolkit to enable the participants to design a 2D tactile display and encourage them to brainstorm for the features they would like to have and (2) gather feedback on how participants perceive the optimal structure for a lo-fi prototyping workshop.

For this purpose, an initial structure for the workshop was defined, aiming to introduce the participants to the toolkit, identify and implement improvements for future lo-fi prototyping workshops, and assess whether participants prefer individual or collaborative work. The structure consisted of an overview of the goals of the workshop, the toolkit, and the software UIs. Followed by an individual design session, where the participants used the toolkit to create their prototypes. Throughout this part of the workshop, the moderator provided guidance and answered questions. The workshop concluded with a feedback session.

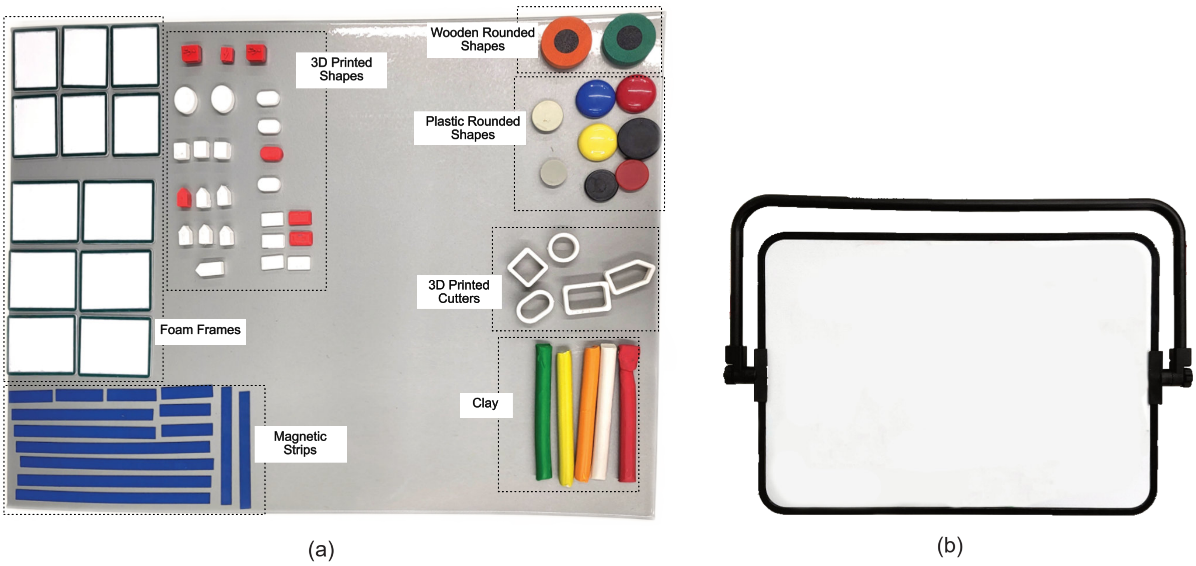


Figure 4.1: (a) Initial prototyping toolkit consisting of various components including 3D-printed shapes, wooden and plastic rounded shapes, 3D-printed cutters, clay, foam frames, and magnetic strips (b) A flat magnetic board for placing the buttons and control elements on it by the participants to design their 2D tactile prototypes during the workshops.

ID	Age Range	Onset	Gender	Familiarity	Frequency of Use	Prototyping Experience
P1	19–28	Birth	M	Familiar	Often used	None
P2	19–28	Adulthood	F	Unfamiliar	None	Participated in a design thinking workshop
P3	29–38	Childhood	M	Familiar	Rarely used	None
P4	39–48	Birth	M	Familiar	Often used	Participated in multiple prototyping workshops

Table 4.1: Demographic participants information regarding their age, gender, familiarity with 2D tactile displays, their frequency of use, and experience with prototyping workshops.

4.2.2.1 Participants

Four participants (three male and one female) aged between 19 to 48 years were recruited, all of whom are blind with varying onset of blindness from birth to later stages of life (as shown in Table 4.1) and all participants except for P2 could read and write Braille. The participants were recruited from an email list of individuals who are blind or have low vision and have previously taken part in accessibility research at Karlsruhe university of technology. The workshops were video and audio-recorded. The study adhered to the ethical guidelines defined by the university.

4.2.2.2 Workshop Procedure and Methodology

Each workshop lasted 90 minutes and included one blind participant and a sighted moderator who took notes during the workshop. The workshops were conducted with participants providing informed consent at the beginning, in accordance with the ethical guidelines of our university. An iterative approach was followed, with adjustments made after each workshop to continuously improve the toolkit. The structure of the workshop consisted of the following three parts:

Part 1: Introduction and Overview - 25 Minutes: At the beginning of the session, the participants were welcomed and introduced to the session's objectives. The purpose of the session was explained, emphasizing the role of the prototyping toolkit in developing tactile display prototypes and the importance of participant feedback for toolkit refinement. Then, the moderator explained the features of the tactile display, the two example software UIs (file explorer and graphics viewer), and the toolkit's components.

Next, the moderator asked the participants about their demographic information, experience with prototyping methods, and familiarity with 2D tactile displays. Participants who had similar experience in designing were asked to reflect on their experiences.

Part 2: Prototyping Session - 45 Minutes: In this session, the participants were given time to explore the toolkit's elements and were asked to use the toolkit to design their 2D tactile display prototype. They were asked to consider how the prototype would function for the file explorer and graphic viewer UIs. The session allowed for hands-on arrangement of buttons and controls on the magnetic board to simulate the 2D tactile display. Participants could seek assistance or clarification from the moderator as needed.

Part 3: Feedback Collection - 20 Minutes: Semi-structured interviews were conducted to gain insights into participants' perspectives on the toolkit and the lo-fi prototyping method. The questions asked in this part included:

- What do you think about the toolkit?
- Do you have any recommendations for enhancing the toolkit?
- Do you have a preference for individual versus group prototyping sessions?
- Are there any recommendations for enhancing the prototyping process?

4.2.2.3 Data Analysis

The workshops yielded approximately 5.9 hours of audio recordings across the four workshops which were transcribed afterwards. The transcribed data, the researcher's observations of participant interactions, and the participant responses from the semi-structured interview formed the basis for the data analysis, which was conducted by one member of the research team. The analysis focused mainly on collecting comments about the feedback regarding the toolkit and the structure of the workshop and the design suggestions and reasons for them.

4.2.2.4 Results

In this section, the design results and a summary the answers of the participants and observations noted during the workshops are presented.

Device Design Feedback: The four participants were able to design their prototypes successfully, as shown in Figure 4.2. P1 mentioned that HyperBraille device has a Braille keyboard which is not ergonomically positioned as it is at the top of the device, which means the user needs to stretch their hands on top of the screen to reach it. Therefore, the participant placed the keyboard at the bottom of the device as shown in Figure 4.2 (a). The participant also mentioned that the device should have a touch sensitive display and suggested an interaction to read certain elements on the screen by placing one finger on the screen and pressing the *"Read Outloud"* button.

The design of P2 shown in Figure 4.2 (b) included a separate area which is pixel-based screen that would be similar to IOS and would be used to display the file system and handle touch interactions and that the tactile area should only be used to display important info which needs to be accessed in a tactile format such as graphs and images. It is worth to note that this was one of the participants who was sighted for most of her life. The participant mentioned that the device should not be cluttered with buttons and should utilize multifunctional buttons, for example the navigation button should be a wheel that can be rotated, push in different directions and also pressed. Additionally, as the participant was interested in adding comments when reading, she suggested implementing a virtual keyboard

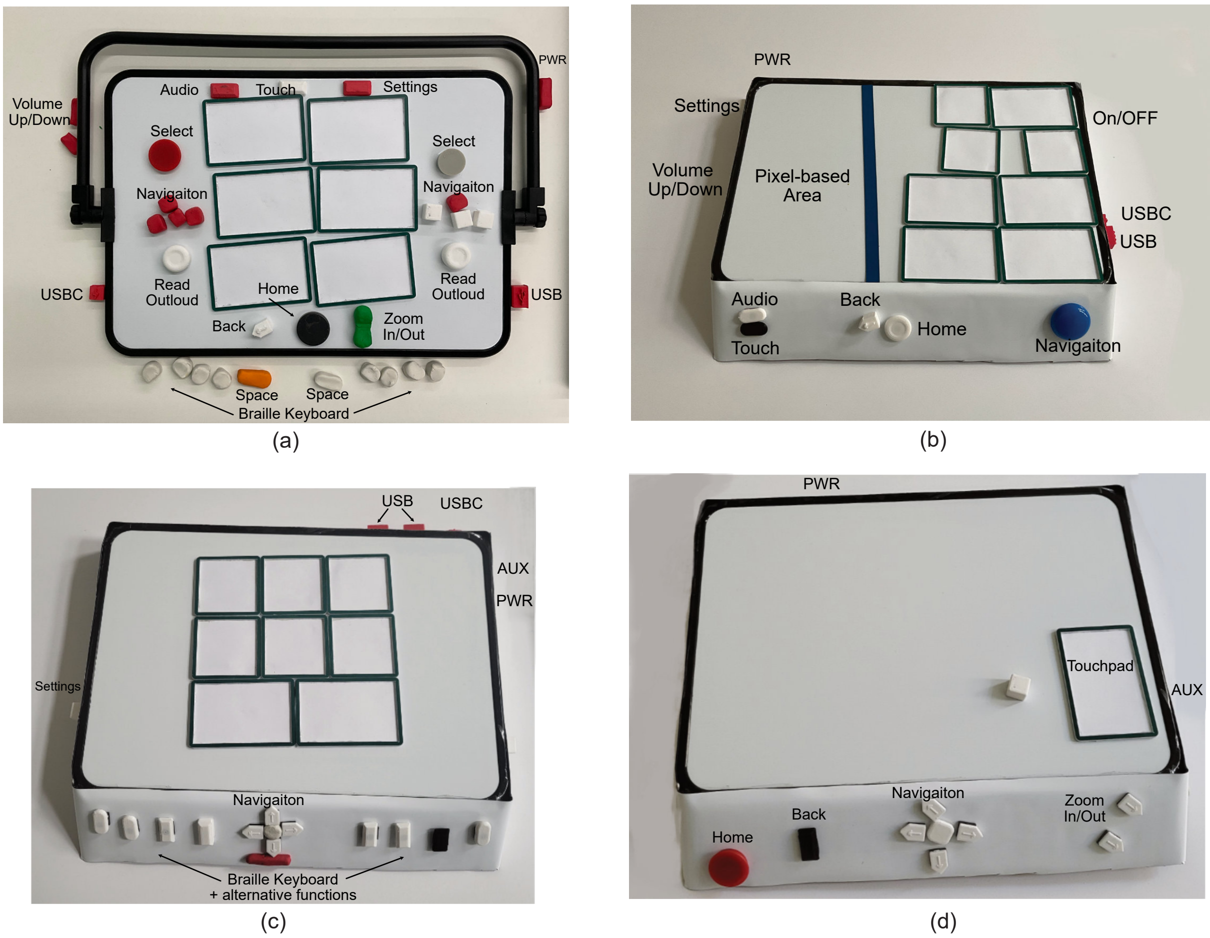


Figure 4.2: The four lo-fi prototypes designed during phase 1, ordered in the same order of the workshops (a), (b), (c), (d).

on the pixel-based area, similar to the phone. The participant suggested including a camera at the back of the device which would allow the user to take photos of documents or images and convert them directly into a tactile format when needed.

The design of P3, shown in Figure 4.2 (c), also favored minimizing the number of physical buttons. As a suggestion for functionality, the participant proposed using the bottom part of the display to present contextual options—such as settings, or, when inside a specific application like the document viewer, to display available actions such as adding comments or changing view modes. The participant emphasized that the device should not include too many buttons, as this could make them difficult to remember. Additionally, they suggested that the settings menu should be accessible via audio feedback and navigable using the available buttons. The participant also expressed a need for configurable buttons, allowing users to assign specific functions to the Perkins-style keyboard keys.

The design of P4, shown in Figure 4.2 (d), included a swipe area consisting of a touch-pad that enabled users to scroll through the settings menu. However, the participant still emphasized the need for navigation buttons, arguing that they would benefit users who are unfamiliar with touch gestures or who prefer more precise control.

Toolkit Feedback: Regarding the toolkit, all the participants provided positive feedback. As for the sufficiency of components and shapes in the toolkit, all participants mentioned that the existing shapes were enough and additional shapes were not necessary.

Two participants (P2, P4) who had previous experience with design workshops reflected on their experiences with the materials in previous design workshops. P2, who participated in a design thinking session, remarked that she was

Participant	Interactions	Device Design & Ergonomics
P1	• Perkins-style keyboard for text input • Physical button to announce on-screen content • Touch gestures for selection and navigation	• Home button located adjacent to the back button • Keyboard positioned at the bottom for improved accessibility • Sloped front surface to support ergonomic typing • Symmetrical button layout • Navigation buttons modeled after conventional laptop keyboards
P2	• Touch gestures inspired by iOS interactions • Virtual keyboard displayed on the pixel-based tactile surface	• Group related functions (e.g., audio and tactile feedback) • Minimize the number of physical buttons (multifunctional controls) • Integrate a rear-facing camera into the device
P3	• Perkins-style keyboard for input • Touch gestures for zooming (similar to iOS)	• Minimize the number of physical buttons (multifunctional controls)
P4	• Touchpad area for swipe-based input • Dedicated physical button for settings access • Navigation using physical buttons	• Route cables to the front or sides to avoid interference with device use
Participant	**Presentation**	**Software Features**
P2	• File system should be displayed on the pixel-based area of the device	• Enable document editing functionality • Ability to add comments to documents
P3	• Allocate a tactile region at the bottom of the screen for secondary options • Audio-based settings menu	• Programmable/configurable buttons

Table 4.2: Summary of participant suggestions for interactions, device design, and software features.

not able to participate in that session due to the dependency on sketching tools, *"That was all using Scratch [digital sketching tool] and involved drawings and such. So, I basically just sat there and could not really participate."*

In contrast, P4 reflected on his experience where he had to manually cut and shape materials like Styrofoam and mentioned that the use of magnets in our toolkit was "more efficient and user-friendly" compared to that approach. P4 added that the other approach was both "time-consuming and less precise".

All four participants commented on the buttons' height, indicating that the original height, ranging from five to ten mm, was too thick. They recommended reducing it to avoid obstructing hand movements during exploration and design and to offer a more realistic tactile experience.

Regarding the materials used in the toolkit, all participants preferred the 3D-printed buttons, noting that their small size made them feel more realistic. P4 specifically mentioned that he did not like using clay, due to its texture. However, the other three participants found the clay useful and recommended that it remains a part of the toolkit.

All participants found it easy to differentiate between the various shapes used in the toolkit. However, one participant (P2) suggested that the buttons, such as the home button, would benefit from tactile markings, saying that this would make collaborative work easier, *"I think you can remember that in your head, if the home button also had a little house icon, that would help. And, yeah, especially if you're doing collaborative prototyping, so others can immediately understand what the button is supposed to represent. It's really helpful if they have some kind of marking."*

As the flat magnetic board given to the participants only allowed components to be placed on the top of its surface, it was noticed that this forced the participants to place elements on the table around the magnetic board. P1 requested to add sides to the board in order to provide a place for placing elements on the sides.

It was also noted that participants frequently had to ask for clarification on how the software UIs functioned. P4 specifically highlighted this issue and suggested incorporating embossed paper into the toolkit to allow them to explore it with their hands.

Workshop Feedback: Participants were asked if they preferred collaborative or individual design sessions. P1 mentioned that he preferred individual sessions, while the rest of the participants indicated that collaborative sessions with a *"maximum of two to three"* participants could be helpful. P2 highlighted that this would be beneficial for brainstorming, *"I think, for brainstorming and exchanging ideas, it's really cool when several people sit together because someone says something, and then you get new inspirations."*

However, P2 also raised a concern that individual voices might be overshadowed by more dominant participants in a group setting:, *"I think you need to ensure that you are not overly influenced by others, so that in the end, everyone does not end up with the same result"*

Participant P4 expressed a similar concern and suggested conducting two individual design sessions in parallel, to allow the participants to speak "more freely", *"Well, you can speak more freely. You know, if you can get two rooms, you can do it in parallel. First, you work on everything and then, after 30 minutes, there's a small exchange where you swap prototypes and the groups can briefly present why they chose certain buttons."*

4.2.3 Incorporating the Feedback to the Toolkit and the Workshop Structure

In this section, a summary about how the toolkit and workshop structure were adapted to the participants' suggestions received from the co-design workshops is presented.

4.2.3.1 Design of the Final Toolkit

As a result of the feedback from the participants, the final toolkit included buttons with a reduced height of two mm (as shown in Figure 4.3 (a)). Additional tactile markings were added on top of some buttons (arrows and USB ports) to facilitate recognizing differences in tactile shapes, as suggested by P2. Additionally, since participants P1 and P4 explicitly requested more buttons during the session, the quantity of each shape was increased to eight. Embossed tactile screenshots of the two software UIs and the features list printed in Braille (as shown in Figure 4.3 (c) was added to the toolkit to help the participants build an idea of how the software UIs look like.

To address the difficulties participants faced when placing buttons on the sides of the device, the case was redesigned as a box with magnetic surfaces on all sides, keeping the same top area but increasing the height to five cm. This new design enabled buttons and control elements to be positioned anywhere around the device. Additionally, based on feedback from two participants (P1, P2), a sloped was incorporated to the front to the new case to enhance ergonomics.

(a) (b) (c)

Figure 4.3: Final prototyping toolkit, (a) magnetic board with 3D-printed elements that represent the buttons and control elements of the 2D tactile display, 3D-printed squares that represent the tactile pins, magnetic strips and clay, (b) a box that represents the future device case of a 2D tactile display made from compressed wood with magnetic surfaces on all sides, (c) two embossed papers representing the available software UIs and printed list of base features of the device in Braille.

4.2.3.2 Improved Structure of the Final Prototyping Workshop

Based on the feedback of the participants, the structure of the workshop was revised to include two parallel individual prototyping sessions, allowing two participants to design independently without external influence. In addition, a new 30-minute collaborative design session was introduced, where the two blind participants could come together to learn about the other blind person's design decisions and then design a common prototype with the agreed features.

In addition to the revised workshop structure, the seating arrangement was also adjusted so that at the beginning, one participant was seated next to their assistant, while the second participant and their assistant sat directly opposite. In the collaborative session, the seats of the two participants were arranged around the corner so that they could show each other their prototypes. This arrangement also supported the design of a joint prototype. The exact settings are displayed in Figure 4.4.

These changes aimed to enable the users to exchange ideas easily, while the small group size was intended to ensure a more inclusive environment where everything was within reach and both participants could contribute equally, reducing the risk of any individual's voice being overshadowed.

4.3 Low Fidelity Prototyping Workshops

The goal of the second phase was to evaluate the refined toolkit and the final workshop structure in a series of design workshops whilst designing a 2D tactile display. For this purpose, six design workshops were conducted over the course of three days with 12 blind participants, two sighted assistants, and one sighted moderator who were all researchers knowledgeable about 2D tactile displays.

4.3.1 Participants

12 blind participants were recruited for the design workshops. The participants were one female and 11 male who were recruited through email lists and during a conference. The demographic information of the participants is shown in Table 4.3. The participants were aged between 19 and 59+. 11 participants were totally blind (eight from birth, two as a child, one as an adult), and one with severe low vision (from birth). All of the participants were familiar with 2D tactile displays and used them before (five rarely, two occasionally, five often).

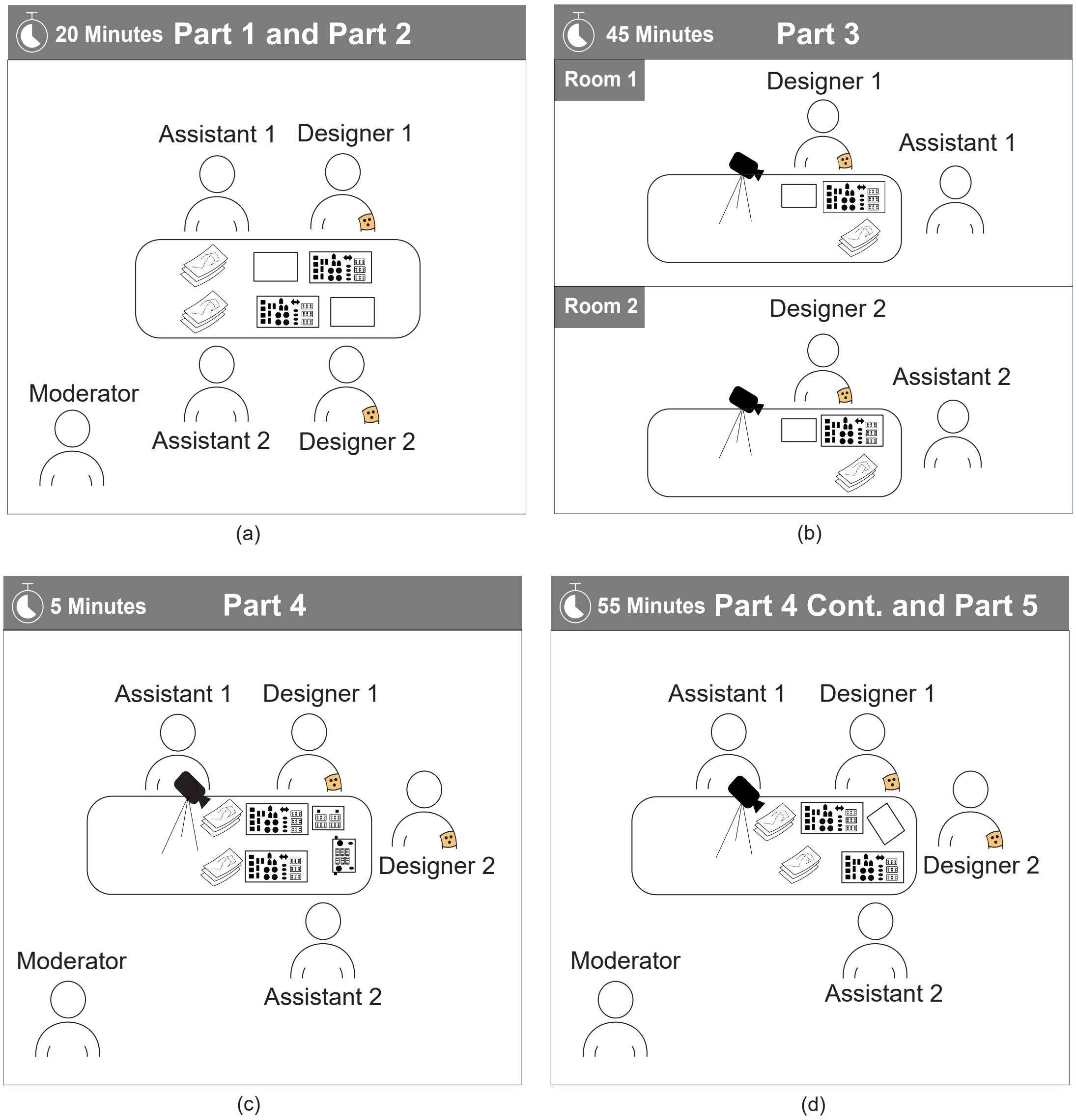


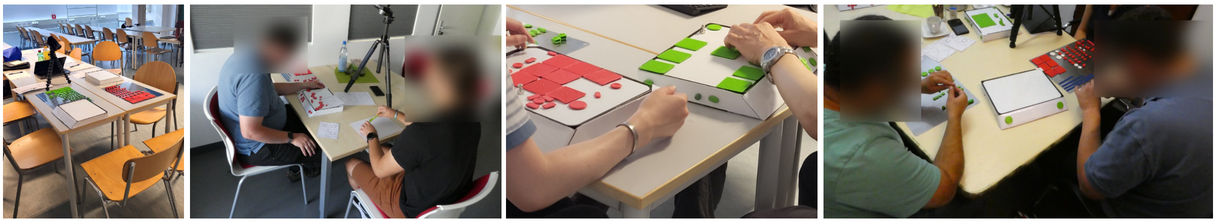
Figure 4.4: The setup used in the different parts of the prototyping workshop. (a) Part 1 and Part 2: the designers, the assistants and the moderator sitting in the same room, (b) Part 3: designer and assistants divided into two groups in different rooms, (c) Part 4: reunion of all designers, assistants, and moderator for the collaboration session. In the first five minutes, the two designers explore each other's prototype while sitting next to each other, (d) Part 4 cont. and part 5: designers working on a common device, followed by the evaluation and feedback session.

4.3.2 Workshop Procedure and Methodology

Each workshop lasted between 120 and 150 minutes. The workshops were organized to include two blind participants, two sighted assistants, and one sighted moderator. The workshops adhered to the ethical guidelines defined by Karlsruhe Institute of Technology (KIT) [145]. Consent forms were sent to participants via email and participants were asked to sign these forms before the beginning of the workshop. The workshops were comprised of five parts: (a) welcome and overview, (b) introduction and material exploration, (c) individual design session, (d) collaborative design session, and (e) evaluation and feedback. All workshops were audio and video recorded, focusing only on the participants' hands. The workshop scenario is described in Appendix A.2.

WS Number	ID	Age	Gender	Usage	Tactile Displays	Vision	Onset
1	P1	39–48	M	Rarely	Hyperbraille	Totally blind	Birth
	P2	39–48	M	Rarely	Hyperflat, Graphiti	Totally blind	Birth
2	P3	39–48	M	Rarely	Hyperbraille	Totally blind	Child
	P4	39–48	M	Often	Hyperflat	Totally blind	Birth
3	P5	49–58	M	Often	Graphiti, Hyperflat, Hyperbraille, Dotpad, Tactonom	Totally blind	Birth
	P6	19–28	M	Rarely	Hyperflat	Totally blind	Birth
4	P7	29–38	M	Often	DotView	Totally blind	Birth
	P8	29–38	M	Often	DotView	Totally blind	Birth
5	P9	59+	M	Rarely	DotView	Totally blind	Adult
	P10	29–38	F	Occasional	DotView	Totally blind	Child
6	P11	29–38	M	Occasional	Dotpad	Severe low vision	Birth
	P12	59+	M	Often	Hyperbraille	Totally blind	Birth

Table 4.3: Information of the prototyping workshop participants. WS = Workshop number.



(a) (b) (c) (d)

Figure 4.5: Insights from the prototyping workshops: (a) preparations, (b) individual design session with a sighted assistant, (c) two participants exploring each other's prototype at the beginning of the collaborative design session, (d) two participants designing one tactile display together during the collaborative session.

4.3.2.1 Workshop Roles

Three key roles were defined for all the participating individuals in the workshop. The roles included, designer, assistant, and moderator. The designers were the participants who are blind or have low vision, and the role of the designer was to design the prototypes. The sighted participants were assigned the role of assistant, which is available to assist the designers if they needed help, e.g., describing where material could be found, handing it over if requested, reading the list of basic features upon request, and answering questions about the task description. In addition, assistants drew sketches of the prototypes and took notes of their observations. However, they were not permitted to offer suggestions or judge the designers' decisions. The moderator was a sighted participant whose responsibilities included explaining the workshop agenda, introducing the toolkit, and collecting participants' feedback during the final session.

4.3.2.2 Part 1: Welcome and Overview - 10 Minutes

In this session, the moderator explained the general purpose of the workshop and gave an overview about the workshop agenda and how much time each session takes. Additionally, the participants were introduced to each other and also to their assistants.

4.3.2.3 Part 2: Introduction and Material Exploration - 10 Minutes

Subsequently, the moderator introduced the features of the 2D tactile display that would be designed during the workshop, along with the prototyping toolkit that would be utilized (as shown in Figure 4.4 (a)). The participants were informed that the new device will initially feature two software UIs: a file explorer and a graphic viewer for interacting with graphics. They were also notified about the potential interactions available in various applications, such as zooming, panning, and selecting. The assistants handed over three embossed sheets of paper to each participant, consisting of the tactile screenshots of the file explorer and the graphic viewer UI (displayed in Figure 4.3 (c)), and a list of the base functionalities and interactions in Braille that should be available in the new device (as shown in Figure 4.3 (d)). The moderator invited participants to add additional features. In addition, the moderator explained the toolkit and detailed the available components, along with the magnetic box that served as the tactile display case featuring magnetic surfaces throughout. The participants were also informed that they could position the buttons on any surface of the box.

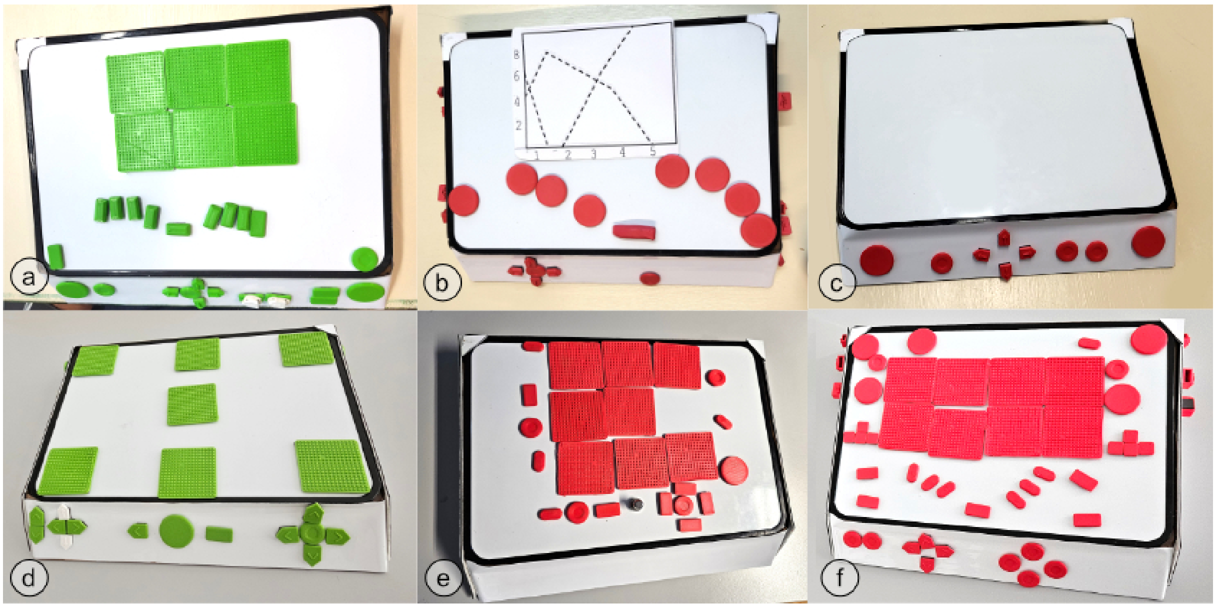


Figure 4.6: Examples of the prototypes created during the individual design session of the prototyping workshops.

4.3.2.4 Part 3: Individual Design Session - 45 Minutes

The participants were divided into two groups in two different rooms, each group consisting of one participant and one assistant (as shown in Figure 4.4 (b)). The participants had 45 minutes to design their prototype. Before the session started, the participants were informed that the assistants would not suggest ideas unless the participants explicitly asked them to do so. Additionally, the participants were told to ask their assistants if they needed assistance or if something was not clear. The assistants were instructed to use the first five minutes to ask the participants about their demographic information and their experience with tactile displays. This was the only active role they had during the workshop. Additionally, each assistant was asked to keep notes or interesting observations and sketches of the prototype designs.

4.3.2.5 Part 4: Collaborative Design Session - 30 Minutes

In this session, both participants were united in the same room (as shown in Figure 4.4 (c)). In the beginning, each participant had the chance to explore the prototype of the other participant for five minutes. Subsequently, each participant was asked to explain their design. After this session, both participants were provided a new magnetic case and a new toolkit and were asked to design a common device using the best ideas they both agreed on (as shown in Figure 4.4 (d)).

4.3.2.6 Part 5: Evaluation and Feedback Session - 20 Minutes

After the participants designed the new device together, they were asked questions about how they would use the new tactile display. Then, the moderator conducted a semi-structured interview with the participants to ask for their feedback and experience during the workshop.

4.3.3 Data Analysis

Approximately 14.5 hours of audio data were recorded from the six workshops. The recordings were later transcribed and analyzed following the open coding analysis approach by [146]. One researcher was involved in conducting the analysis, which yielded 259 first level codes which were later iteratively collated into sub categories and resulted in the following final four core categories: (a) Workshop structure and Dynamics, (b) prototyping toolkit usability, (c) design challenges and usability issues and (d) user-centered design and novel software capabilities, as shown in Table 4.4. The four categories offer a detailed understanding of the experience of the users while prototyping and insights about the collaborative work dynamics and the role of the sighted assistants. The core categories are discussed in the following section.

4.3.4 Results

All participants successfully designed their prototypes, incorporating all the features outlined in the features list shown in Figure 4.3 (d) and additional features they wished to include. Figure 4.6 shows some prototypes created during the individual design sessions.

4.3.4.1 Workshop Structure and Dynamics.

The participants reported high levels of satisfaction with the prototyping experience and having the chance to design their own ideas or what they wish to have in the device. For example, P10 described the workshop as *"...really fun, imagining and creating the devices that I want to exist."*. Similarly, P12 emphasized the novelty of the experience, stating, *"It was brilliant. It was a nice idea because it's the first time in my life that I've designed hardware.*

All participants expressed that both single design and collaborative design sessions were useful and they liked the combination of both sessions. For instance, P12 appreciated the balance of independent thinking followed by collaborative idea integration, *"It's a good process. It's a good idea to have two individuals first independently and then take the ideas and unite them. We have a good ratio between what each individual took from the other."*

Core Categories	Description
Workshop Structure and Dynamics	Findings related to the workshop structure, timing, facilitation, role of sighted assistants, and collaboration on task performance.
Prototyping Toolkit Usability	Challenges and feedback regarding toolkit usability, including memory and cognitive demands, and accessibility of the components and materials used in the toolkit.
Design Challenges and Usability Issues	Participants' insights into ergonomic and usability challenges, as well as limitations of current tactile devices.
User-Centered Design and Novel Software Capabilities	Creative input on future opportunities, design preferences, and accommodating varying user needs.

Table 4.4: Summary of core categories from workshop data analysis.

This sentiment was confirmed by P11, the only participant with severe low vision, who emphasized that collaborative working with other participants provides a good chance for the participants to understand the different needs of blind and low vision users, *"I think especially because with blindness, low vision, everyone's needs are so different. I think it's definitely good to have it separate first so that you get a chance to kind of think it through yourself and then present with someone else's, that shows you someone else's needs. And then you kind of combine them both."*

Collaborative dynamics often involved hands-on guidance, with participants physically directing each other's attention to specific features of their prototypes, when they needed to explain certain details.

Some challenges were observed due to language barriers, particularly when participants were native speakers of different languages (WS3) or when English was not their first language (WS4, WS5). In contrast, communication was smoother among participants who were already acquainted, as seen in WS1, WS2, and WS4. This familiarity led to longer and more in-depth discussions during the design process.

Sighted assistants played a pivotal role in supporting participants, particularly in aiding in understanding the tasks. Several participants (P3, P6, P9, P12) asked their assistants to remind them of the functions of some buttons they had placed. Some participants also requested assistance obtaining certain buttons or creating shapes using clay. Additionally, participants sought clarification from their assistants on the functionalities that were not clear to them. For example, P1 mentioned in his feedback he appreciated the accompany of the assistant as it was particularly helpful in explaining the zooming concept, which he was unfamiliar with, *"I actually had some problems, particularly with Zoom thing, it's difficult for people who don't know exactly what it is. So, I asked my assistant and he explained it"*.

Although some participants had different purposes in mind for the devices they designed, they could effectively merge their objectives during the collaborative session. For example, during WS5, P9 envisioned the new display as an extension to a computer for displaying graphics and drawing purposes, making including a keyboard or audio output unnecessary, as the computer would manage these functions. In contrast, P10 took a different approach with her device as she mentioned that she preferred a standalone, portable device and emphasized that there are many tactile devices that can be connected to computers, but she preferred a more independent solution. Also, in WS4, P7 expressed a strong interest in designing a device optimized for gaming, whereas P8 focused on developing a tool for drawing and viewing graphics.

Some participants experienced initial confusion about the objectives of the workshop. Participants (P1, P2, P4, P12) expressed confusion about the initial workshop's goal, particularly regarding whether they were supposed to design the layout of the software UIs or only the device itself. One participant (P12) mentioned being overwhelmed due to the short introduction time, *"based on the introduction that was given, I was overwhelmed by the sheer number of objects and I needed some time to perceive."*

The same participant also suggested providing the initial introduction, shown in Section 4.3.2.3, as a digital or paper document so that the participants could read the introduction in their own time before or at the beginning of the workshop.

The assistants reported that several participants expressed concerns during the individual design sessions about not being creative enough. Additionally, some participants conveyed insecurities regarding the aesthetics of their designs. Some participants occasionally sought confirmation from the assistants on how to approach certain tasks.

One participant (P8) suggested that future workshops could benefit from grouping participants based on their interests, such as those inclined toward designing a drawing device versus those interested in a gaming device.

Regarding the time allotted for the sessions, most of the participants finished within the session time. However, during the collaborative design sessions, participants of one workshop (WS3) were not able to finish within the allotted time.

4.3.4.2 Prototyping Toolkit Usability.

Regarding the design and usability of the lo-fi prototyping toolkit, most of the participants found the magnetic components easy to use and appreciated the variety of shapes included. P2 highlighted the usability of the magnetic board, stating, *"A reasonable idea for using such a magnetic system. Because it's very simple, and I can put and remove the elements immediately.*"

Some participants suggested areas for improving the toolkit. For example, two participants (P7, P8) noted the absence of triangle-shaped buttons, while participants P1 and P12 mentioned that they did not like the feeling or touch of clay and asked the assistant to form the clay shapes for them when it was needed.

4.3.4.3 Design Challenges and Usability Issues.

Participants highlighted several design challenges related to the ergonomics and usability of current 2D tactile displays. Key considerations included balancing compactness with usability, particularly in providing sufficient space for displaying larger graphs. The mobility of the device was another critical aspect, along with other practical concerns such as device positioning and compatibility with external commonly used tools like keyboards. Additionally, participants emphasized the limitations in existing devices, particularly regarding cost and functional shortcomings, highlighting a gap between current designs and user needs and expressing a demand for more accessible and user-centered solutions.

4.3.4.4 User-Centered Design and Novel Software Capabilities.

During the workshops, participants provided a broad range of suggestions related to interaction methods, device design and ergonomics, and software functionality, as detailed in Tables 4.6, 4.5, and 4.7, respectively.

In terms of device design and ergonomics (Table 4.5), recommendations focused on optimizing physical controls and layout. Key proposals included minimizing the number of physical buttons by employing multifunctional controls, incorporating joystick and rotating wheel mechanisms for volume and audio feedback, and using physical scroll bars. Participants emphasized tactile differentiation through textured or curved buttons and preferred a symmetrical device design with strategically positioned buttons, such as a Perkins-style keyboard located at the bottom. Connectivity preferences, such as Bluetooth over cables, and portability were also highlighted. Furthermore, participants suggested maximizing the device's tactile display area within a rectangular form factor smaller than A4 size.

Regarding interaction concepts (Table 4.6), participants proposed various input methods, including virtual keyboards, Perkins-style keyboards, and combinational buttons for secondary functions such as “alt” and “ctrl.” Additional suggestions encompassed touch-based interactions like pixel-based gesture areas and zoom/selection gestures, as well as external keyboards and pointer controls akin to a mouse.

Concerning software functionality and features (Table 4.7), participants expressed interest in programmable buttons and application development, including drawing tools and games. They also proposed a centralized application hub or app store to facilitate streamlined access to software, device connectivity to computers, and support for keypads capable of handling both numeric and Braille input, similar to older phone models.

Device Design & Ergonomics	
No. of Participants	**Suggestion**
4	Minimize the number of physical buttons through multifunctional controls
4	Joystick control
2	Rotating wheel for volume adjustment and audio feedback
2	Physical scroll bars (horizontal and vertical)
2	Buttons differentiated by curvature or texture
2	Aux port and cables positioned near the front
4	Symmetrical device design
1	Limit to no more than three buttons clustered together
2	Prefer Bluetooth connectivity over wired connections
5	Perkins-style keyboard positioned at the bottom of the device
2	Portable device design
3	Maximize device area dedicated to data presentation
8	Rectangular tactile area smaller than A4 size

Table 4.5: Summary of device design and ergonomics suggestions.

Interaction Concepts	
No. of Participants	**Suggestion**
3	Virtual keyboard interface
7	Perkins-style keyboard
4	Combinational buttons for secondary functions (e.g., Alt, Ctrl)
1	Pixel-based touch-sensitive area for gestures
4	Touch gestures for zooming and selection
1	Virtual buttons located at the bottom of the screen for thumb use, for application-related settings
4	External keyboard for text input
2	Movable pointer on the display, similar to a mouse cursor

Table 4.6: Summary of interaction suggestions from participants.

Software Functionality and Features	
No. of Participants	**Suggestion**
7	Programmable buttons
5	Drawing application
2	Games
1	Centralized application hub (app store)
1	Device connectivity with computers
1	Keypad supporting numeric and Braille input (similar to older phone keypads)

Table 4.7: Summary of software functionality and features suggested by participants.

4.4 Discussion

This section, presents answers to the research questions in section 4, and reflect on the insights gained from the analysis of the conducted workshops.

RQ1: How can lo-fi prototyping methods be adapted to effectively involve blind individuals in the design of accessible technologies?

The findings from the second phase of workshops emphasize the value of early user input from Phase I in adapting the materials and shaping a toolkit aligned with participants' needs. Key refinements, such as reducing the height of 3D-printed elements, were driven by participants' feedback to ensure a realistic tactile experience and unobstructed hand movement, which are changes that are specific to this target group. They contributed to the creation of an easy-to-use toolkit, which allowed participants to focus on brainstorming and conceptualizing features without being hindered by the mechanics of material creation. This contrasts with the findings of Metatla et al. [139] that lo-fi prototyping can pose difficulties that impede participants' ability to concentrate on key aspects and express their ideas.

The results of the workshops indicated that using embossed paper to represent software UI layouts, as demonstrated by Miao et al. [134] and suggested by a Phase I participant, was helpful for most participants in understanding the software interfaces presented. It was also observed that incorporating embossed paper to explain complex concepts, such as zooming and panning, is important particularly during early design stages when the software is not fully developed and functional prototypes are unavailable. Since many blind individuals are familiar with static tactile materials like swell or embossed paper, including these elements in the toolkit can be highly effective for communicating software concepts during the early prototyping stages.

On the other hand, the toolkit proposed in this work may be viewed as a constraint that influenced participants' creative processes, the role of constraints in fostering creativity has been widely discussed in design research. For example, Mose Biskjaer et al. [147] demonstrated that creativity constraints and radical decision-making can sometimes lead to original design solutions, avoiding dead ends and potentially accelerating the design process. In this regard, our observations showed that the boundaries set by the toolkit and materials in our study did not hinder participants' ability to innovate. Instead, they focused participants' attention on functionality and usability, particularly in relation to assistive devices, and prevented them from becoming overwhelmed by unrestricted design possibilities.

The seating arrangement during the workshops was also noticed to positively impact the individual and collaborative sessions. Seating participants beside their assistants during individual sessions enabled material handling and immediate support when requested. Similarly, in collaborative sessions, seating the participants around a corner facilitated hands-on collaboration and enhanced communication and teamwork by allowing participants to easily guide each other's hands on the prototype and exchange elements with their collaborators.

RQ2: How to structure prototyping workshops to prioritize blind users, and what roles should sighted assistants play?

Collaborative sessions can be challenging, as Brewer [142] noted that collaborative design sessions involving blind participants can lead to individual ownership of designs rather than a genuinely collaborative outcome. In contrast, our workshops showed that the collaborative sessions were highly enjoyed by the participants. This can be due to the fact that each session included only two blind participants, which likely mitigated some of the challenges Brewer identified. By maintaining a more focused environment, each participant had the opportunity to fully present and discuss their ideas. Additionally, when we asked the participants about their preferences they expressed appreciation for having both sessions, as they valued the chance to first work independently before coming together to integrate their ideas.

As the design sessions were kept open to encourage participants to propose additional features and applications, it was noticed that this can lead to creating devices tailored to different purposes. While this flexibility can encourage brainstorming and generating innovative ideas, it can also present challenges in collaborative settings, as participants may struggle to agree on a unified final design. It was also noticed that some participants requested to start with the predefined features list to kickstart their design process. This suggests that while open-ended design is valuable, providing structured guidance alongside it can better support participants in starting and generating ideas. This finding aligns with the work of Magnusson et al. [140], which emphasized the importance of well-defined roles and structures to facilitate effective discussions among participants. The study conducted in this chapter extends these insights by showing that it would be beneficial in future prototyping workshops to group participants based on their interests or needs. For instance, participants who shared a common need, such as a device for gaming or drawing, would be able to collaborate more effectively if grouped together.

Several participants (P1, P2, P7, P8, P9, P11, P12) noted that the allocated time for the collaborative design session was insufficient. Similarly, some participants mentioned that the introductory session was not long enough to understand all the details. Therefore, extending the introduction session to include more details about the goals and what is expected from the user in the workshop or alternatively, as suggested by one participant, providing a written pre-workshop introduction outlining the goals can be used. However, sending a pre-workshop description in advance may result in participants investing varying amounts of time in preparation, as some may review it at the last minute, while others may not engage with it at all, leading to differences in their prerequisite knowledge [148]. A possible solution is to provide a written description with the introduction at the beginning of the workshop, allowing everyone to review it at their own pace, as suggested by P12.

To prioritize blind participants as the primary contributors in the design workshops, the role of sighted assistants was limited to providing explanations, clarifying doubts, and assisting in navigating through tasks that may be difficult to grasp without sight. This was helpful when participants encountered difficulties with concepts they were not familiar with. Additionally, it underscored the need for sighted assistants to be well informed about the topic and prepared to offer clear, patient explanations. Furthermore, when participants struggled to recall design choices, such as the specific functions assigned to each button in complex designs, the help provided by the assistants, who relied on their notes or drawings, proved to be highly valuable.

This minimal intervention approach can still influence workshop outcomes. For instance, when assistants provide feedback, whether positive or negative, this can bias participants' responses, leading them to adjust their actions to align with what they believe is expected. For example, positive feedback, even a (dis)consenting muttering, might reinforce their current approach, discouraging them from exploring alternative solutions. Therefore, it is recommended to establish clear guidelines for the assistants' role. Specifically, assistants should maintain a neutral position and avoid expressing emotions or opinions that could be interpreted as feedback and focus on providing objective support, such as clarifying tasks or helping with technical aspects.

Assistants also observed that some participants expressed concerns about not being creative enough. This could be due to unfamiliarity with prototyping which led them to assume that the workshop's goal was to create an aesthetically pleasing final product. To address this, assistants should provide additional support throughout the workshop by reassuring participants that the primary goal of prototyping is not the aesthetics or final appearance of the designs, but rather the exploration of ideas and concepts.

Recommendations for Future Lo-Fi Prototyping Workshops In this section, we share our recommendations to support accessibility researchers and designers for structuring lo-fi prototyping workshops with blind participants, based on our observations and findings across both phases of workshops. These recommendations focus on creating workshop environments that prioritize blind participants' input and creative contribution to the design process.

1. **Design of the Materials:**
    - Utilize materials from previous research with the target group, as a foundation for discussions, and refine them together with the target group before their employment in the final design workshops.
    - For complex software concepts, consult multiple people from the target group to determine how best to explain these aspects in the final workshops.
2. **Structure of the Workshop:**
    - Combine individual and collaborative prototyping to encourage idea exchange while allowing participants to work at their own pace.
    - Allocate sufficient time for the introduction to explore the toolkit and address questions.
    - Share the workshop agenda with participants in advance.
3. **Workshop Environment:**
    - Provide a textual description of the task which can be read at the beginning of or during the workshop at their own pace.

- Seat participants next to each other during collaborative sessions.
- Group participants based on their needs to facilitate effective collaboration.
- Address language barriers to ensure clear communication.

4. **Role of Sighted Assistants:**
    - Clearly define the assistants' role, emphasizing minimal intervention and avoiding feedback.
    - Assistants should be familiar with the topic to be able to answer any questions.
    - Assist participants by documenting design elements (e.g., using notes, drawings, photos) to aid recall.

4.5 Limitations

With respect to the methodological approach presented in this chapter, future work needs to address few shortcomings and open questions concretely identified and already discussed in the previous section, in an effort to fine-tune participant experience. Here, the role of sighted assistants should be the focus point of additional research: In our work, their behavior was not always consistent and may have impacted participants' experiences. In this context, an additional limitation to be considered is the specific participant group involved in our research. In the first phase in particular, only a small number of participants (four participants), and while this is acceptable in the context of our qualitative research approach, future work should involve people who are blind or have low vision more broadly to ensure that the methodological approach is widely accessible. Here, special attention should be paid to achieving gender balance, i.e., involving more women and non-binary persons.

Another limitation is that participants were not provided with existing 2D tactile displays. This decision was made to prevent influencing the workshop outcomes and avoid potential bias toward designing similar displays. Additionally, the logistical challenges and high costs associated with transporting such devices posed significant barriers to scalability and accessibility. However, the absence of hands-on experience with the actual devices may have limited participants' understanding of the technology's capabilities and constraints, potentially affecting the feasibility and practicality of their design ideas.

4.6 Conclusions

This chapter introduced a lo-fi prototyping methodology to enable users who are to participate in the early design stages of assistive devices. The research approach was conducted in two phases: the first phase involved workshops with four blind participants to design a lo-fi prototyping toolkit and refine the structure of the workshops. The second phase focused on conducting hands-on prototyping workshops with 12 blind participants. These workshops included individual and collaborative tasks between two participants to design prototypes of 2D tactile displays using the toolkit that we designed in the first phase.

The findings highlighted several key advantages of our prototyping approach. It enabled the participants to take an active part in adapting the design method and in the design process, thus making an important contribution to the development of 2D tactile displays. Participants generated numerous additional ideas beyond the initial list of functions provided to them and effectively communicated their preferences for future design features. However, some challenges were also identified, particularly concerning time constraints, which affected participants' ability to fully understand the workshop objectives and optimize their contributions.

Despite these challenges, the new approach highlights the potential of lo-fi prototyping for blind individuals as a valuable tool in the early design stages of assistive technologies if the method and toolkits are adapted to their needs. The contributions of this chapter lay a foundation for future research to refine this approach, ensuring that blind users can play an even more active role throughout the design process, not just during evaluation.

5 Design and Development of a Portable 2D Tactile Display

This chapter builds on the results of the prototyping workshops presented in Chapter 4, and presents the process of developing a hi-fi prototype of a new 2D tactile display. The prototype is based on one of the designs created by the 16 blind users, who were involved in the prototyping workshops. It also incorporates the findings from Chapter 3, namely the TUIs designed for presenting documents and graphical information on 2D refreshable tactile displays. The chapter begins with a brief comparison between lo-fi and hi-fi prototyping, followed by an analysis of existing literature relevant to designing 2D tactile displays.

The contributions of this chapter are the following:

- The design and development of a hi-fi prototype of a portable 2D tactile display, incorporating hardware and software co-designed with participants who are BLV.
- Design and development of a new file system TUI for 2D refreshable tactile displays that allows users to interact with files directly on the device.
- The insights from a formal study with nine blind users on evaluating the designed prototype.

5.1 Context

In contrast to lo-fi prototyping approaches which focus on simplified and often static representations of the final system, hi-fi prototyping involves creating functional, interactive versions that closely approximate the final product in appearance and behavior [149]. Both prototyping approaches serve complementary roles within the design process [131]. Lo-Fi prototypes, typically constructed from simple materials with minimal interactivity, facilitate early communication of design concepts. Their simplicity and rapid iterability make them particularly suitable for quickly gathering ideas and making the stakeholders not focus on the deep details, rather the overall design [150]. Additionally, creating lo-fi prototyping encourages hands-on experimentation without requiring complex technical setups or programming skills [131].

However, lo-fi prototypes often lack the capacity to capture the nuanced behaviors of a final system, such as responsiveness, precise audio-tactile feedback, and timing of interactions [151]. To overcome these shortcomings, hi-fi prototyping becomes beneficial in later design stages. By simulating or implementing key system functionalities, hi-fi prototypes enable realistic interaction testing, behavioral exploration, and identification of usability challenges that emerge only in operational systems. Within the HCI field, hi-fi prototyping is widely recognized for its role in producing visually, structurally, and functionally accurate system simulations [151]. It is particularly valuable in later design phases where precise evaluation of interaction flow, feedback mechanisms.

Despite growing interest in 2D tactile displays, the literature offers limited guidance on designing either hi-fi nor lo-fi prototypes of 2D tactile displays. One of few works by Magnusson et al. [152], introduced a co-design approach using lo-fi materials such as embossed paper and 3D prints. Their study used Wizard-of-Oz techniques to simulate interaction on 2D tactile displays, enabling discussions about multimodal feedback. However, while their approach emphasized user involvement, the description of workshop tasks and methods lacked detail, making it difficult to replicate or generalize.

Similarly, Bornschein et al. [153] explored tactile input control layouts by adapting elements from pther existing tactile displays. In this study, six blind participants tested different input configurations on the BrailleDis 9000 display [70]. While informative, the study focused on evaluating predefined control mockups, without offering participants the opportunity to influence the design in real-time or reconfigure the layouts.

In the following sections, an approach to designing a hi-fi prototype of a portable 2D tactile display is presented.

5.2 Portable 2D Tactile Display Software Design and Development

The goal of this dissertation is to co-design a new 2D tactile display that supports independent use by users who are BLV and facilitates access to digital information commonly used in STEM fields. Accordingly, the design requirements for the new display were informed by an analysis of prior work on TUIs and the feedback and suggestions received from the participants involved in the evaluation process (Section 2.7.1), insights gained from the co-design workshops with participants who are BLV (Chapter 4), and feedback collected during the design of the three TUIs presented in Chapter 3. The following section describes these requirements in detail.

5.2.1 Requirements of Integrated Portable 2D Tactile Displays

Real-Time and Continuous Feedback. To support orientation and build user confidence while using the display, immediate feedback is essential, as demonstrated in the evaluation results of the TUIs presented in Chapter 3. The system must provide tactile and audio responses for all user actions, such as selecting elements on the display, receiving notifications, and informing the user of any changes that occur in the device in a real-time manner. This feedback is critical for confirming actions and maintaining a clear understanding of the system's current state.

Maximizing Tactile Display Area with Minimal Physical Controls. Participants in the prototyping workshops (Chapter 4) emphasized the importance of maximizing the tactile display area to present content clearly, while simultaneously minimizing the number of physical buttons. Reducing physical controls helps decrease cognitive load by avoiding the need to memorize numerous button functions. To balance these needs, virtual or audio-based menus should be favored, allowing efficient access to settings without compromising the tactile display space and cluttering the display.

Personalization Options. The device should support a range of personalization options, including remapping button functions according to the preference of the user, possibility to define shortcuts. Additionally, the ability to choose the representation language such as 6-point or 8-point Braille, contracted and non-contracted, as well as the language of the device and screen reader and controlling the speed of the screen reader.

Integration with other Assistive Technologies. To fit into users' existing ecosystems, the device should be compatible with screen readers (such as Apple VoiceOver) and external assistive devices. This cross-device integration ensures accessibility and usability across both mobile and desktop platforms. Also the possibility to connect one-line Braille display or a keyboard depending on the usecase.

Connectivity and Access to Digital Content. Expanding the device's functionality beyond offline use by integrating both Bluetooth and Wi-Fi capabilities to enable connection to wireless headphones or other wireless devices. Wi-Fi access to enable the users to upload, download, and organize files via cloud platforms.

Offline Access and Local File Storage. While cloud connectivity is valuable, the ability to store and manage files directly on the device remains essential. Users must be able to save documents, graphics, and other materials locally for reliable access regardless of internet availability. This ensures that the user can use the device in any environment with limited or no connectivity.

Support for Diverse Application Domains. User requirements for tactile displays span a broad spectrum of activities, including but not limited to reading, gaming, and web navigation. Therefore, the device architecture should be designed with modularity and extensibility in mind, allowing for the integration and deployment of multiple TUIs tailored to distinct application domains. This flexibility ensures that the device can accommodate evolving user needs and support a wide range of interactive tasks relevant to users who are BLV.

5.3 Design of a File System Tactile User Interface for 2D Tactile Displays

Building upon the design principles and requirements outlined in the previous section, the development of a TUI for file management is critical to enable users to efficiently navigate and organize digital content on the 2D tactile display. The following sections detail the design and implementation of a file system TUI designed for 2D refreshable tactile displays.

5.3.1 Directory Structure in the File System

The implementation of the file system for 2D tactile displays follows a modified Linux Filesystem Hierarchy Standard (FHS). The system includes five main directories: */home*, */bin*, */sbin*, */etc*, and */opt*, as shown in Figure 5.1 each serving specific purposes as explained in the following sections.

(a) home Directory: The */home* directory stores user files and personal configurations. Following UNIX conventions, application configurations are stored in hidden directories that begin with a period ('.'). For single-configuration files, they're stored directly as '.fileName', while multiple configuration files are organized within a '.fileName' directory.

(b) bin and sbin Directories: The */bin* directory contains user-executable programs while the */sbin* directory includes system binaries critical to the tactile OS functionality, including, tactile feedback driver management scripts, input port monitoring daemons that process new data added to the device, programmable button configuration tools, document segmentation scripts used for converting newly added files to a tactile format.

(c) etc Directory: The */etc* directory stores system-related configuration files, including, tactile representation libraries, audio files used for multimodal feedback, user preference profiles and storing system settings.

(d) opt Directory: The */opt* directory serves as the installation location for third-party TUIs. Each application is installed in its own subdirectory (e.g., '/opt/EPUBViewer' for a EPUB document interface) with a standardized structure that separates executable files and application-specific resources.

5.3.2 Tactile Representation of Files and Folders

To support intuitive navigation within the file system TUI, considering how to represent files and folders using tactile symbols is important. Prior research has shown that recognizing tactile symbols on refreshable 2D displays can be challenging for users who are BLV. Factors such as shape complexity, number of edges, and size significantly affect recognition accuracy and speed.

A relevant study by Leo et al. [154] explored how users interpret 16 distinct tactile shapes, categorized as U-, L-, T-, and O-shaped symbols. These were displayed on a 30×32 pin tactile display. Each symbol was tested in two sizes: 3×3 and 4×4 pin grids. The study found that U- and O- shaped symbols were most accurately and quickly identified, especially in the larger 4×4 format. Visually impaired participants made no confusions between U- and O- shaped symbols, while one blind user confused these two.

This work drew from these findings to guide the tactile design of the UI elements in the file system TUI. U- and O-shaped symbols were used for folders and files due to their strong performance in recognition, specifically, an open U-shape was used to represent a folder and a closed O-shape to represent files. Additionally, a blind user, who is familiar with multiple 2D tactile displays was consulted while designing the interface by providing him with embossed screenshots of the TUI. The suggestions received from the user included the following:

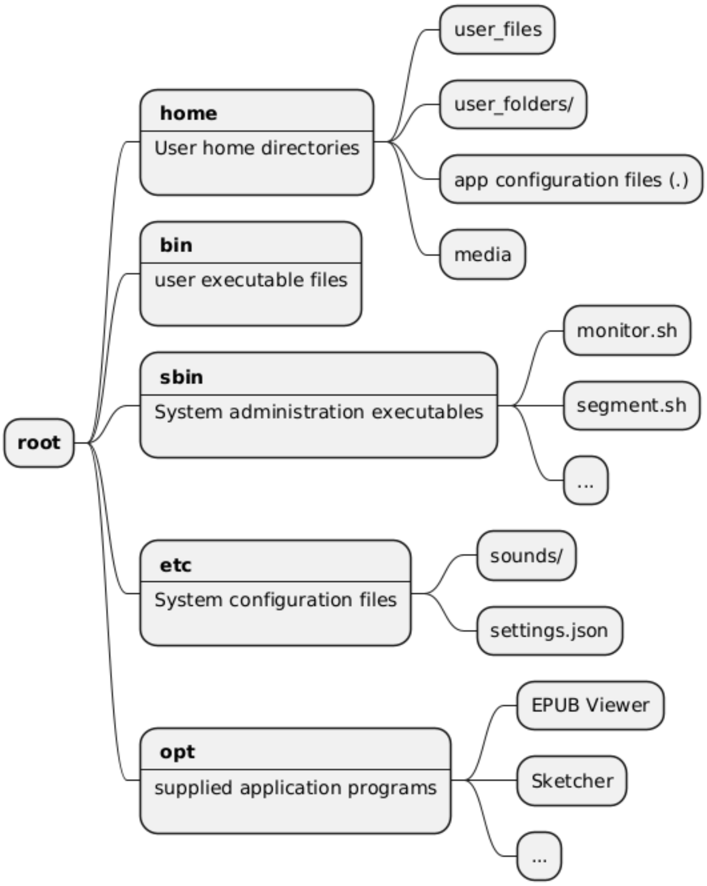


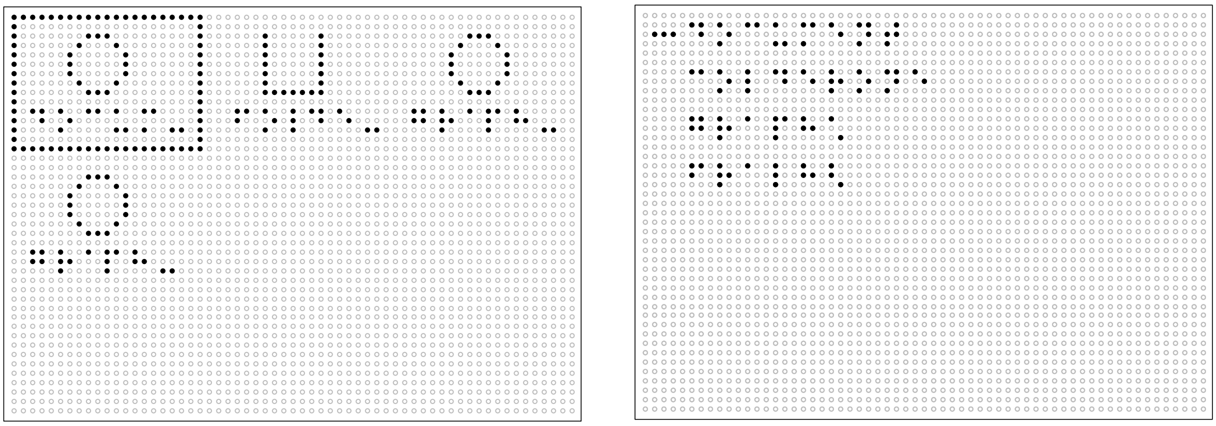
Figure 5.1: Tactile file system hierarchy consisting of five main directories.

1. Adjustment to the size of the icons to 7x7, and adding enough spacing between the tactile icons for improved distinction.
2. Adding file names under the icons.
3. Adjusting the name of the icon and adding a hyphen to indicate long names.
4. Including an optional mode for presenting the icons' names as a list.
5. Implementing touch and buttons navigation options in the TUI.

5.3.2.1 View Modes

The results of the tests with the blind collaborator led to the following two distinct view modes in the file system TUI:

(a) Icon View: Files and folders are arranged spatially in a grid-like format, as shown in Figure 5.2 (a). In this view mode, files are represented as circular icons, while folders are represented as U-shaped icons, indicating they contain additional files or sub-folders. Each symbol is created with a size of 7x7 pins. In this view mode, file names are restricted to five Braille letters and exceeding this limit, the interface employs tactile-optimized abbreviations by appending a hyphen at the end of the name to indicate that the full name extends beyond the displayed portion, as shown in Figure 5.2. In this mode, highlighting a file or a folder occurs by displaying a tactile box around the element.



(a) (b)

Figure 5.2: Tactile representation of the file system: (a) icons mode represents the files and icons using circle and u-shaped icons, (b) list view mode displays the files and folders as text list.

(b) List View: Files and folders are displayed in a linear list, as shown in Figure 5.2 (b), where the files are arranged according the date of creation ascending. This view modes makes it possible to display more files and folders in one screen. However, as only the name of the files is available, it is not possible to differentiate between folders and files. In this view mode, highlighting a file or a folder creates a short tactile line consisting of three pins to the left of the file. The dimensions are adjusted to the 2D tactile display used for testing the file system TUI, which is the HyperBraille display [69], the dimensions and spacings in each view mode are shown in Table 5.1.

Parameter	Icon View	List View
File Arrangement	Grid	List
Sorting Method	Tree structure	By creation date (ascending)
File/folder distinction	Yes (tactile shapes)	No
File Representation	Circular (files), U-shaped (folders)	File name
Title Length	5 Braille cells + 1 hyphen	screen width / Braille cell width + 1 spacing - 3 pins padding (left)
Vertical Spacing	2 rows	2 rows
Horizontal Spacing	2 columns	Not applicable
Top & Bottom Padding	2 rows	1 row
Highlighting Method	Bounding box	a line with three dots length to the left of the name

Table 5.1: Comparison of the two view modes implemented in the file system TUI: the icon and list View modes and the corresponding dimensions when running on HyperBraille display [69].

5.3.2.2 Navigation and Interactions

The navigation in the file system TUI is implemented using either physical buttons or a combination of touch interaction and button presses.

(a) Button Navigation: Initially, navigation using buttons was implemented by enabling the user to press a select button, which would highlight the first element. This approach was inspired by how blind users interact with

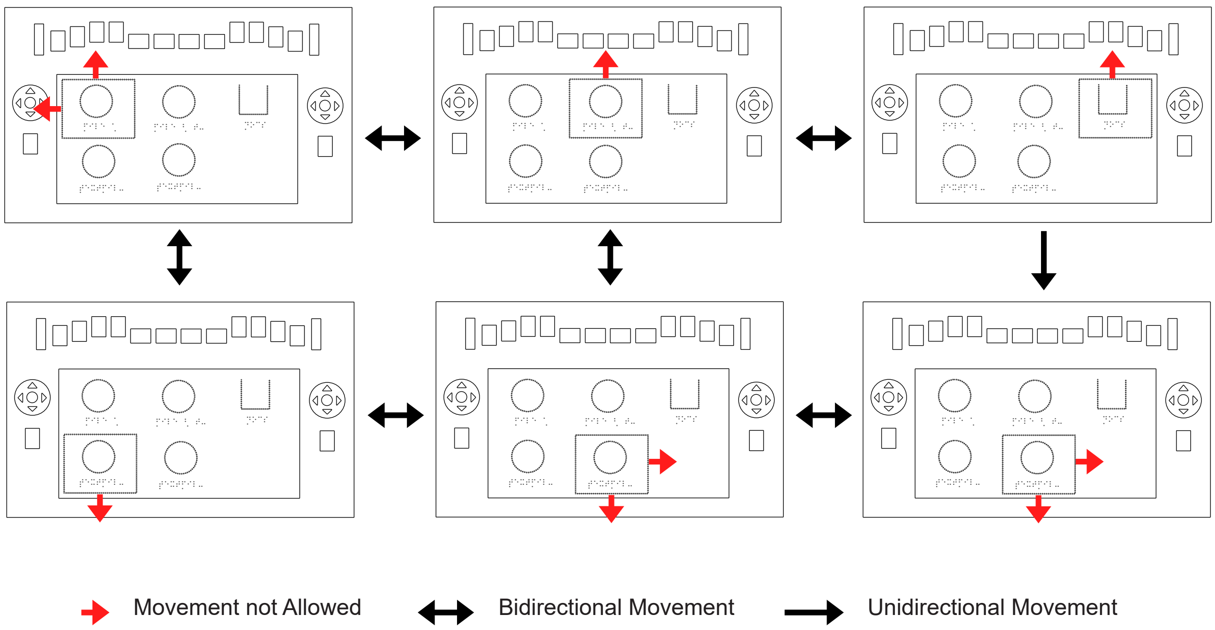


Figure 5.3: File system navigation mechanism using buttons. Black arrows indicate valid directions for movement, while red arrows represent invalid directions that trigger an audio error signal to the user.

smartphones, where a single tap highlights an item and a double tap activates it. Different navigation methods were implemented for icon and list view modes. For example, pressing the directional navigation buttons in the list view moves the dashed line to the next element bellow the currently highlighted element. In the case of the icon view mode, the navigation depends on the file or folder highlighted, as shown in Figure 5.3. When the user reaches the edges of the screen this is explicitly communicated by certain audio signals. For instance, attempting to navigate in the directions highlighted in red in Figure 5.3 would trigger a distinct audio signal indicating a crash to inform the user that further navigation is not possible.

(b) Touch Navigation: With touch navigation, the user can place a finger on either the file's icon or its name and open the file by pressing a physical button. In addition to an audio signal indicating the end of the list, another audio cue confirms when the selection moves between different files.

5.3.3 Device Settings and GUI Implementation

To support the development process and facilitate collaboration, a GUI was created to simplify development and allow for testing the interaction concepts without requiring constant access to the physical 2D tactile display. It serves two main purposes:

1. **For developers:** The GUI offers a visual representation of the tactile interface, allowing developers to preview layouts, test interactions, and develop accessible applications without requiring access to a physical 2D tactile display during the development process.
2. **For sighted collaborators:** The GUI provides a digital, text-based view of the same content shown on the tactile display, offering an alternative to Braille. It also enables interaction via touchscreen, supporting collaboration with users who are BLV by making the interface content understandable and accessible to sighted users.

The GUI implements the following three view modes:

1. **Braille Light:** Displays the tactile representation in a bitmap format for fast representation of the view provided to blind users.
2. **Braille Detail:** Shows the tactile format view but with more details such that each individual pin/taxel can be seen. This view aims to provide a more detailed view which can be beneficial to sighted developers for debugging purposes.
3. **Pixel:** Displays the same content displayed to blind users but in the pixel format. This mode is intended for collaboration purposes, where the sighted users can navigate or select files using this GUI.

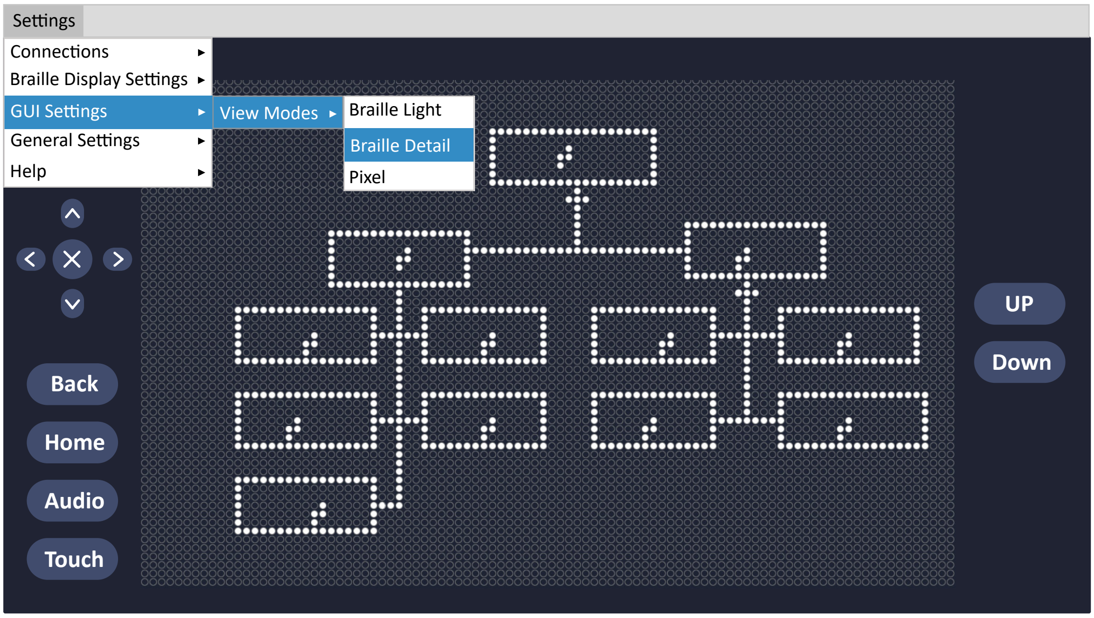


Figure 5.4: Screenshot form the GUI showing the graphical viewer in the Braille detail view mode.

The GUI replicates the physical controls of the 2D tactile display, allowing users to perform navigation and interaction tasks in the TUIs. Additionally, a settings menu, illustrated in Figure 5.4, is provided. This menu includes options for Bluetooth and Wi-Fi connectivity, Braille display settings that allow users to switch between different view modes such as icon and list view, and GUI settings for accessing the three view modes described in the previous section. It also includes general settings for configuring the device language and screen reader preferences, as well as a help button that offers contextual information about the current screen or relevant TUI features, as detailed in the document TUI section in Chapter 3. The same settings menu is available to users who are BLV, presented in an audio-based format.

5.4 Design of the Physical Interface and Controls

In this section, the process followed to transition from the lo-fi prototypes, presented in Chapter 4, to the hi-fi prototype of the 2D tactile display. This process began with analyzing the various designs and categorizing these designs, identifying patterns, and understanding common preferences. Based on these insights, the designs were grouped into clusters leading to the development of four distinct design prototypes. The following section presents these design clusters and the rationale behind each of the final prototypes.

5.4.1 Analysis of Low Fidelity Prototypes

Based on the results from the two studies presented in Chapter 4, the designs created by participants during both individual and collaborative design sessions were analyzed. In the first study, four designs were produced, while the second workshop produced 18 designs, including 12 individual designs and six collaborative designs.

5.4.1.1 Categorization of Tactile Area Placement

It was observed that participants varied in their selection of tactile pin size and placement on the display. The prototypes that were designed can be categorized into five main groups according to their tactile aspect ratio (width-to-height ratio), as illustrated in Figure 5.5. These designs include: (a) pins placed on the right side of the display, (b) pins positioned on the left side, (c) pins centered on the display, (d) pins located at the top, and (e) the entire top section of the device filled with tactile pins.

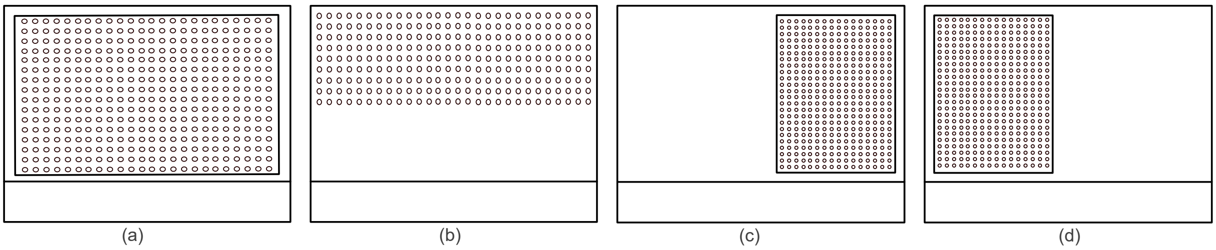


Figure 5.5: The final five designs from the workshops: (a) tactile display as half the top part of the device, (b) the tactile pins placed only at the half left part of the device, (c) the tactile part as a center part of the device, (d) the tactile pins placed at the right side the device.

5.4.1.2 Categorization of Control Elements Placement

Regarding the placement of the device controls, the following categories were observed:

1. Groups for Cognitive Mapping: It was observed that some users tended to organize buttons based on their cognitive associations and functional relationships. For example, buttons with similar functions were often grouped together. For example, the audio feedback button was frequently placed near the AUX port and volume buttons, indicating a preference for proximity to related controls. Similarly, buttons for touch feedback were often placed near audio feedback control. Back buttons were also often placed near the home button which resembles modern smart phones in the design.

2. Preference for Fewer Physical Buttons: A recurring suggestion from users was to introduce virtual buttons accessible via the device's software. For example, some users proposed grouping functions like settings, volume control under one virtual menu. This could be accessed through a screen-based interface, making it easier to manage multiple functions. Users also suggested replacing the physical keyboard with a virtual one. This virtual keyboard would be similar to mobile phones that it could be displayed on-demand via the menu or a dedicated physical button, allowing for flexibility while minimizing the need for additional hardware.

3. Placement for Ergonomics: Several users expressed specific preferences for button placement, emphasizing ergonomic considerations for ease of use. For example, many participants recommended placing frequently used buttons on the front of the device for easy access during use. However, some participants cautioned against placing any buttons on the front, fearing accidental presses while handling the device.

In terms of cable management, users suggested that cables, particularly the AUX port for headphones, should be placed on the sides of the device, near the front, to prevent interference with the tactile surface. This would ensure that cables do not obstruct the user's interaction with the display. Conversely, power cables and USB ports should be positioned at the back of the device or the back ends of the sides to prevent them from obstructing the hands when pressing buttons on the sides of the device.

For those participants who preferred not to have an integrated keyboard, they suggested that if an external keyboard was connected, it should be placed near the side or back of the device. This would keep the keyboard accessible but not intrusive, preserving the device's ergonomic design.

Additionally, a number of participants emphasized that all buttons should be within reach if the device is designed to an A4 size, ensuring that users can easily access all controls regardless of the device's orientation. Specifically, they recommended avoiding placing buttons at the back of the device, as this would make them harder to reach.

Several participants also highlighted the importance of ensuring that the device is accessible to a wider range of users, including those who are left- or right-handed, by ensuring that button placement is symmetrical to accommodate both right- and left-handed users.

5.4.1.3 Clustering and Finalizing Lo-Fi Prototype Designs

Based on the tactile area placement, the placements of buttons and controls were analyzed and clustered across all participant designs. This clustering process allowed to identify common patterns in button positioning, ensuring that the final prototype would reflect the preferences of the majority. This approach helped pinpoint the areas that participants found most intuitive and comfortable for interaction.

Figure 5.6 shows the results of this clustering process, with the final button placements for each design visualized. Each design represents the most common configuration of buttons and controls, based on the choices made by participants during the workshops.

5.5 High Fidelity Prototype and Hardware Development

This section details the design and development of the hi-fi prototype, based on the design shown in Figure 5.6 (a), which was chosen by the majority of participants in the lo-fi prototyping workshops. However, due to the unavailability of the tactile pins at the time of evaluation, an alternative approach was followed to overcome this problem. Instead of integrating a built-in tactile pins, the prototype was adjusted modified by removing the integrated tactile area, resulting in a compact device. Such that this compact device can be attached to an existing tactile display that was available, which is the HyperBraille display [69]. For this purpose, the ports and buttons previously positioned on the back of the prototype were relocated to the right and left sides while maintaining their relative arrangement. The adjusted design is shown in Figure 5.7.

5.5.1 Choice of Hardware and Enclosure

As the device needed to support WiFi and Bluetooth communication and since the system included an additional GUI for developers and sighted collaborators, it was necessary to select a hardware platform that is capable of running GUI applications efficiently. Given that the hi-fi prototype was intended for further testing rather than extensive redesign, minimizing development time was also a key consideration. For this reason, two hardware platforms were evaluated: the Raspberry Pi and the ESP32-S3.

Both the ESP32-S3 and Raspberry Pi 4 were considered as potential platforms for the prototype. The ESP32-S3 is a power-efficient microcontroller with built-in WiFi and Bluetooth. However, based on the comparison between both

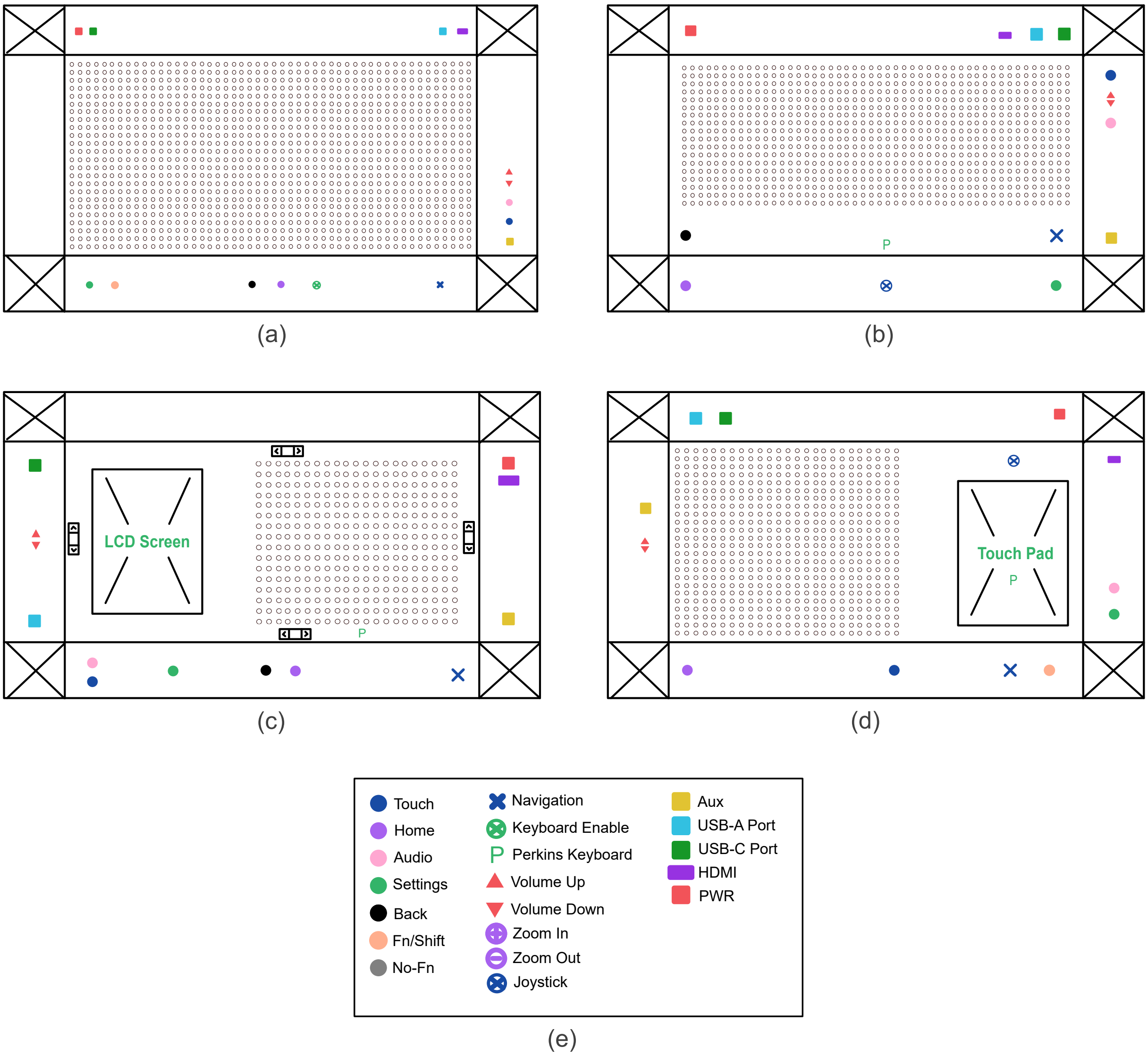
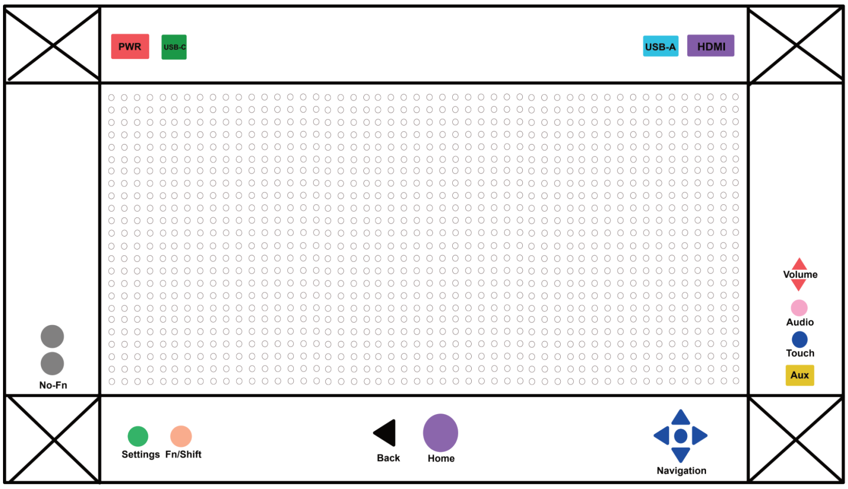


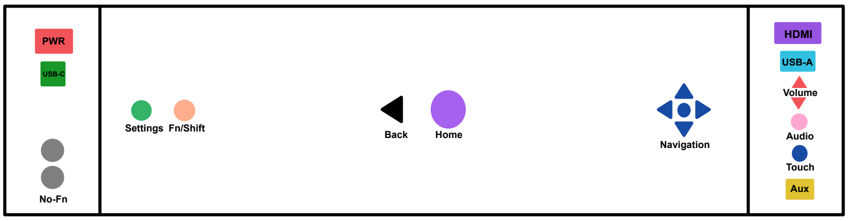
Figure 5.6: The four prototypes created by participants during the prototyping workshops after clustering the buttons and controls of the different participants. (a) First design: tactile pin area centered on the device. (b) Second design: tactile area also centered, but with a more limited interaction region. (c) Third design: includes an additional LCD screen positioned above the tactile area, on the left. (d) Fourth design: features a touchscreen pad located to the right of the tactile area.

systems as shown in Table 5.2, Raspberry Pi 4 was chosen due to its ability to support GUI-based applications, and simplify software development. Its higher processing power and larger memory make it more suitable for handling document rendering and real-time interactions with the tactile display.

The enclosure of the device was fabricated using 3D-printed PLA (Polylactic Acid). The physical buttons included markings for differentiating them from other buttons, such as the power buttons, the volume up and down and the home button. Additionally, the buttons were produced of flexible PLA for a better grip and feel. Also a soft rubbery material was used at the bottom of the device to avoid movement of the device when the users press the side buttons.



(a)



(b)

Figure 5.7: Adjusted design of one of the 2D tactile display prototypes designed by the users in the lo-fi prototyping workshops.

Aspect	ESP32-S3	Raspberry Pi 4	Relevance to the Prototype
Processing Power	Dual-core Xtensa LX7 (240 MHz)	Quad-core Cortex-A72 (1.5 GHz)	The prototype needs to handle a GUI and real-time interactions, requiring higher processing power.
Memory	512 KB SRAM + external PSRAM	2GB, 4GB, or 8GB LPDDR4	GUI applications and tactile user interfaces require more RAM for smooth operation.
Storage	External SPI Flash (limited)	microSD card (expandable)	The prototype needs sufficient storage for firmware, document files, and interface elements.
Connectivity	WiFi 4, Bluetooth 5.0, BLE	WiFi 5, Bluetooth 5.0, Ethernet	Both support wireless communication, but the Raspberry Pi offers better networking capabilities.
Peripheral Support	Multiple GPIOs, I2C, SPI, UART	Multiple GPIOs, I2C, SPI, UART, USB	Both support necessary network connections.
Power Consumption	~300 mW (very low)	~3W idle, ~7W load	The ESP32 is more power-efficient, which means battery usage can be an option.
Ease of Development	Requires firmware development (Arduino, FreeRTOS)	Runs full OS (Linux-based, Raspberry Pi OS, Ubuntu)	The Raspberry Pi allows faster software development using standard tools and libraries.

Table 5.2: Comparison between ESP32-S3 and Raspberry Pi 4 for the 2D tactile display prototype

5.6 Evaluation

An evaluation study was conducted with nine blind participants to evaluate the device. The goal was to assess the accessibility of the device, determining whether users can navigate the applications effectively, and explore the usability of the device as a standalone 2D tactile display. The participants were not all Braille readers, however, the feedback of non-Braille readers was valuable, as 2D tactile displays are also means for providing graphical information and not only text-based information.

5.6.1 Participants

Nine Participants were invited though the university mailing lists. Table 5.3 summarizes key demographic details of the participants, including information about their age range, gender, educational background, and prior experience with 2D tactile displays. Only one of the participants was not familiar with Braille language. Most of the participants (7 out of 9) were familiar with 2D tactile displays and have at least tried them before.

Participant	Age	Gender	Onset	Braille Experience	2D Tactile Displays
P1	49-58	M	Chidlhood	6,8 point	HyperBraille, Tactonom, Dotpad, X-oldDevice
P2	19-28	M	Birth	6,8 point	HyperBraille, Tactonom, Dotpad
P3	19-28	M	Birth	6,8 point	HyperBraille
P4	29-38	F	Birth	6 point	HyperBraille, DotPad, Tactonom, Graphiti
P5	19-28	F	Adulthood	None	None
P6	0-18	M	Childhood	6,8 point	None
P7	59+	M	Birth	6,8 point	HyperBraille, Tactonom
P8	49-58	F	Birth	6,8 point	HyperBraille (Rarely), Vario-Ultra (Daily)
P9	29-38	M	Adulthood	6 point	None

Table 5.3: Demographic data of the participants in the evaluation study.

5.6.2 Material

For the study, The experimental setup is illustrated in Figure 5.8 was used. The setup consisted of the 2D tactile tablet prototype placed in front of the HyperBraille display, which was used as the tactile area of the new device. A wooden enclosure was created in order to seal the existing controls of the Hyperbraille display and allow participants to focus on the tactile area only without being distracted by the current buttons existing on the HyperBraille display. Additionally, an external touch display was connected to the device to provide a GUI for the moderator. This allowed the moderator to observe participants' interactions, assist when necessary, and ensure the correct functioning of the system throughout the study.

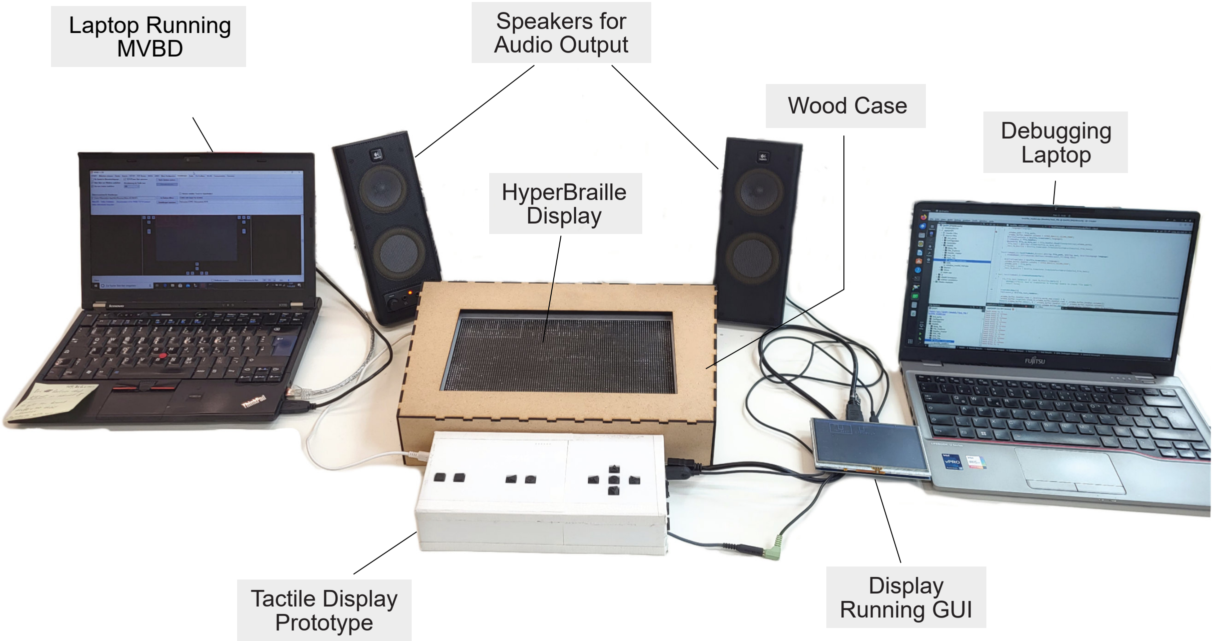


Figure 5.8: The test setup used for evaluating the hi-fi prototype.

5.6.3 Procedure

Each session involved one blind participant and a sighted moderator, and lasted between 1.5 to 2 hours. The sessions were comprised of four parts:(a) introduction and overview (20 minutes), (b) demonstration tasks (30 minutes), (c) Evaluation tasks (30 minutes), (d) Feedback Questions (30 minutes).

In the introduction and overview, the participant was explained the general purpose of the study and given an overview about the structure of the study and the consent of the participant was obtained. Next, demographic information, including age and education, were collected. The participant then received an introduction to the device, covering the three TUIs available, and control buttons of the device. The participant was given time after explaining each side of the device to explore more and ask questions.

Following the introduction and overview, the participant was guided through three tasks designed to familiarize them with the device's navigation methods, available software applications, and basic settings menu. The tasks included navigating to a certain file and opening it, activating the touch settings from the settings menu and finally navigating to a file and extratcting certain information.

After the demonstration, the participant was given four tasks to complete independently without assistance. The first task was related to the navigation and opening a graphic file on the device. The second task was related to enabling the touch functionality of the device through the use of the settings menu. The third task was related to using the graphic viewer to explore a line plot graph and then explain the graph. In the fourth ts, the participant was asked to switch to the list view mode and navigate to a document. finally, in the last task the participant was asked to use the document viewer to read the document and explain the content of the document.

For each task the completion time and success rates were recorded, observations were noted down regarding any challenges noticed or any feedback was given from the participant.

Finally a semi-structured interview was conducted, allowing participants to reflect on their experience using the device and suggest improvements. Additionally, participants complete the NASA-TLX and SUS questionnaires to assess cognitive load and overall satisfaction.

5.6.4 Results

All participants successfully completed the four tasks. The average completion times were 105 seconds for Task 1, 128 seconds for Task 2, 39 seconds for Task 3, and 56 seconds for Task 4, as shown in Figure 5.9. While these averages suggest that Tasks 3 and 4 were completed more quickly overall, several outliers were observed. For instance, in Task 1, P5 took 222.59 seconds to complete the task. Similarly, in Task 3, P7 required 121 seconds, and in Task 4, P8 recorded the longest completion time at 116 seconds.

Regarding user satisfaction, the average SUS score was 85.4%, indicating a high level of usability across participants, with only one participant scoring below 70%, as shown in Figure 5.10 (a). The results from the NASA-TLX assessment, which measures the workload across several dimensions [155], were as follows: the mental demand was rated at 20%, physical demand at 15.6%, temporal demand at 17.8%, performance at 80%, effort at 25.6%, and frustration at 13.3%, as shown in Figure 5.10 (b). These values suggest that while the participants reported some mental and physical effort, they experienced a generally positive perception of performance and low frustration levels.

The recordings obtained from the study, along with the observations taken were later transcribed and analyzed following the open coding analysis approach by Tracy [146]. One researcher was involved in conducting the analysis, which yielded 132 first level codes which were later iteratively collated into sub categories and resulted in the following final five core categories: (a) device design aspects, (b) interactions and presentation, (c) tactile and audio feedback preferences, (d) need for modern AI capabilities, and (e) additional software applications. The core categories are discussed in detail in the following section.

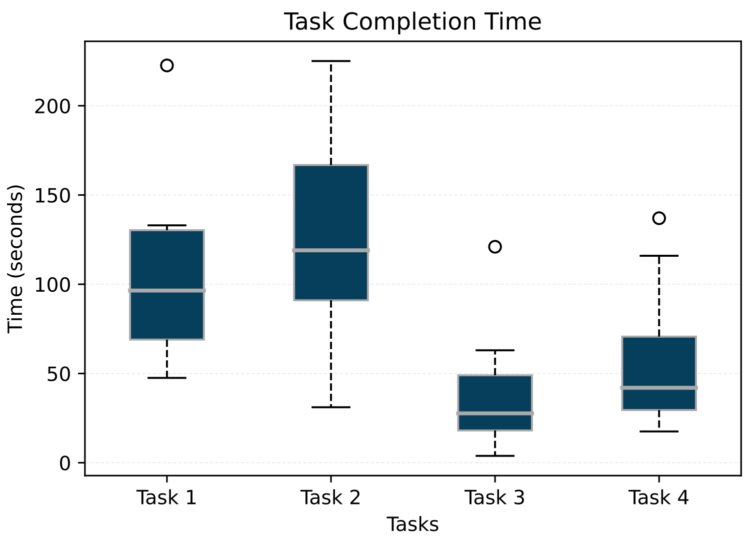


Figure 5.9: Time taken by the participants to finish the four tasks

(a) Device design aspects: All participants stated that the device design was well-executed. However, P1 suggested increasing the size of the buttons, while the rest of the participants found the current size to be sufficient and did not need any changes. Regarding button shapes, only P3 suggested that certain buttons, such as volume up and down, could be replaced with tactile symbols for plus and minus instead of distinct button shapes.

Similarly, P8 suggested that buttons close to each other, such as the audio and touch feedback or settings and shift should have different shapes. The participant suggested that one button can be rotated 45 degrees to differentiate it or using a Braille letter as marking for example, audio buttons would have the letter *A* while touch would have the letter *T*.

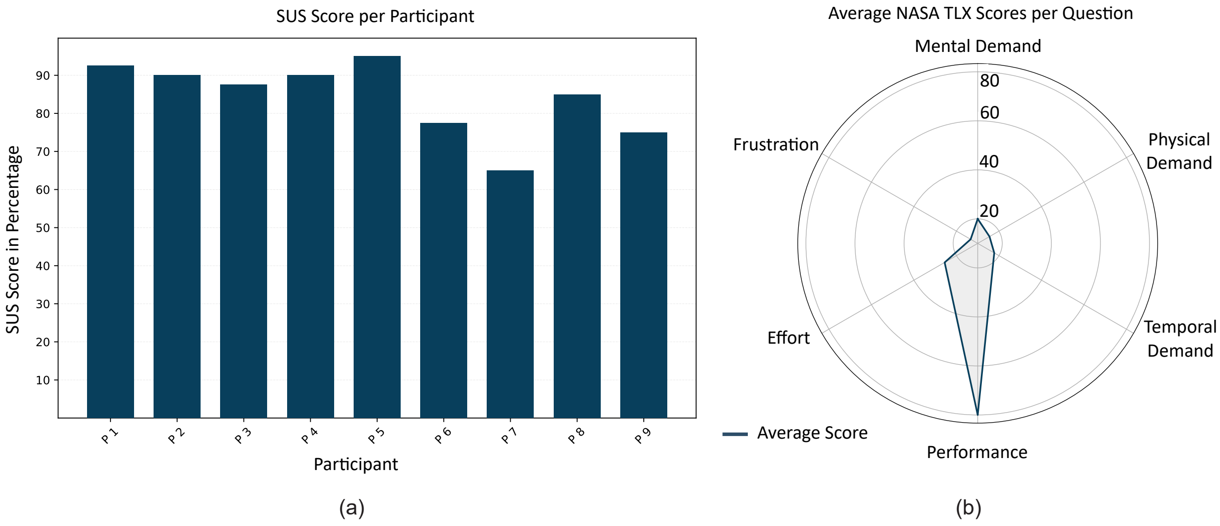


Figure 5.10: Evaluation results : (a) the SUS scores per participants. (b) Radar graph showing the NASA TLX scores per question.

P7 mentioned that the buttons and logically placed which he appreciated. However, the participant mentioned that for him it is necessary to have longer time to memorize all the buttons and that there were many buttons used. However, the user mentioned that it would be enough to use it few times to get used to the buttons and mentioned that he faced similar situation when he started using iPhone in order to get used to the new system and the navigation which he currently highly appreciates.

P2 also recommended implementing feedback buttons, such as those for audio and touch, on both sides of the device. This would allow users to keep one hand on the display while using the other to press buttons. Additionally, it was observed that P4 faced difficulty maintaining one finger on the screen while pressing a button, as she had to cross her arms to do so.

Despite this, P4 expressed strong appreciation for the device's design, particularly the logical arrangement of the buttons. She highlighted that grouping the back and home buttons together, placing the audio feedback button near the volume controls, and positioning both touch and audio feedback buttons close to each other contributed to an intuitive and user-friendly experience. She also noted that the limited number of buttons made it easier to remember their functions.

Furthermore, P4 and P5 emphasized the importance of a compact, portable, and lightweight design for daily use. P4 mentioned that such a device would be highly beneficial, allowing her to carry it easily and use it in various settings, such as lectures. The same comment was received from participant P8 who mentioned that the size of the device should not be bigger than the size of a standard tablet to be able to carry it anywhere around. The same participant mentioned that she needs such a small device for taking notes, everywhere she goes. P7 also confirmed that the size of the device should be small to be able to carry it and use it anywhere and that it should not be bigger than a personal laptop.

(b) Interactions and presentation: P2 and P3 mentioned that highlighting an element first by pressing the select button was not intuitive, as it required an extra step each time. To address this, P2 suggested that the first element should be highlighted by default so that pressing the right button, for example, would immediately highlight the second element.

Regarding the settings menu, all participants stated that they had no difficulties navigating the menus and found the audio-only format sufficient. However, P2 expressed a preference for an additional tactile representation of the menu on the display, implemented in the same way as the list view. P2 also appreciated that the menu does not allow overflow navigation, meaning that once the last element is reached, pressing the down button does not cycle back to the first element. The participant noted that some programs include this feature, which he finds too complex.

P7 and P8 highlighted that they faced challenges understanding if settings menu is open or closed which they preferred to have an option to indicate to the user if the settings menu is still open. Additionally, P8 mentioned that another challenge when the settings menu is only available in audio, is that some feedback is required to indicate what the current status of the settings is, for example, if touch is enabled or not and if the device language is set to English or other language.

P3 and P5 suggested implementing a settings menu specific to each application. This menu would be also accessible only through audio, but should be dedicated to the application-specific functionalities. For example, in the document TUI, this menu should include options for navigating between pages, jumping to specific headers, or searching for a particular page number or text. Additionally, the menu would include features, such as intelligent document summary.

P4 and P6 and P8 expressed interest in using gestures for device control. P4 and P6 mentioned that double-tapping would be useful for opening files or elements, while P8 mentioned that implementing the zoom function in the graphic TUI using gestures would be useful.

(c) Tactile and audio feedback preferences: P1 expressed preference to the list view mode, mentioning that it is helpful as it enabled him to navigate quicker through the different files than the icon view mode. Similarly, participant P2 mentioned that the list view mode would be his favorite when using the device. However, the participant mentioned that both modes are useful and should be both available. The reason for this is the fact that the icons view mode can help blind users build a mental image of the available files and folders when the user does not know what files exist on the device, as the symbols can be then helpful for that purpose. So for this participant, the method of using the device would be to first use the icons mode until familiar with the files and the structure then switching to the list view mode later to be quicker with the navigation. As for P3, the participant also mentioned a preference for the list view mode due to it's similarity with the list view mode in windows OS.

Two participants (P2, P4) mentioned that the information on the display should not be presented too close to the edges of the screen, mentioning that this makes it difficult for reading and suggested leaving two empty lines.

P3 commented on the device's screen reader, noting a preference for Apple's version because it sounded more human-like. However, the participant acknowledged that the current TTS voice can sometimes be useful for quickly reading text. They also suggested adding an option to adjust the screen reader used in the device, as well as the speed.

(d) Need for modern AI capabilities: P3 expressed strong interest in integrating AI features into the device, particularly within the document viewer. He suggested implementing an option to select an image within a document and send it to ChatGPT [102] to obtain additional information. Furthermore, he highlighted the potential of sending both the image and the document together to generate semantic insights about the image's context within the document. He explained that this could be particularly beneficial when the image alone is too complex to interpret in a tactile format.

However, P3 also emphasized that displaying the graphs in a tactile manner remains essential, especially when users are already familiar with the graph and only need specific details, such as peak values in a line graph or key intersection points. Additionally, he suggested implementing an AI-powered document summarization feature to help users quickly grasp the main content of a document.

Similarly, P4 expressed interest in AI capabilities, particularly for accessing additional real-time information about images, including those embedded within documents. The participant noted that existing applications, such as *Be My AI* [156], could be valuable if integrated into the device, as they offer detailed, real-time descriptions of visual content.

(e) Additional software applications: P2 expressed interest in an application that could display matrices in a tactile format, allowing users to explore numerical data more effectively. Additionally, he envisioned a future version of the device that could replace current digital tablets by integrating applications such as a music player and messaging apps, making it a more versatile tool for daily use.

P3 suggested that the current control scheme is ideal for gaming, making the device suitable for interactive experiences. He mentioned that, with appropriate software, the device could support simple tactile-based games, enhancing its usability beyond productivity and accessibility functions. Similarly, P4 emphasized the importance of internet connectivity, stating that the ability to browse the web and access emails would be a high priority, particularly if the device remains portable. She mentioned that with internet access, the device could replace her computer for many daily tasks, reducing the need for additional assistive technology. Editing Capabilities

P2, P3, and P4 all expressed strong interest in adding editing features to the document viewer, particularly the ability to insert comments. P2 emphasized that, for him, the most important feature would be the ability to sign documents, either by directly signing on the device or by inserting an image of a signature. P5 also mentioned that an application for drawing directly on the display would be useful. P7 mentioned that he would like to use the device for reading as the participant mentioned that reading on 2D displays for him is quicker than on 1D tactile display.

One participant (P3) emphasized the importance of connecting the new tactile display to a personal computer to dynamically load and explore data. He illustrated its potential during tasks such as training an AI model, where he could examine outputs like confusion matrices or other graphs in a 2D tactile format. Similarly, P4 considered PC connectivity valuable, particularly when the device lacks internet access, as it would allow her to use the display primarily for viewing documents in a tactile format.

5.6.5 Discussion

This study has provided valuable insights into the design, development, and potential future applications of 2D tactile displays. The feedback from the users who are BLV, along with the iterative design process, allowed for continuous refinement of the prototype, addressing any challenges that was faced by users. The lessons learned from this process can inform future developments in the field of assistive technology for individuals who are BLV.

The co-design approach with the end users through the process of designing lo-fi prototypes of the device not only ensured that the technology met their needs but also fostered a sense of ownership, which was shown by the high rates of SUS scores shown in the previous Section 5.6.4. Many participants noted that the buttons were arranged logically across the device, with related controls grouped together, which was a design choice originating from blind designers involved in the lo-fi prototyping process. These decisions contributed to a device that allowed users to focus on its capabilities rather than expending excessive effort on learning its operation, as evidenced by the low mental demand and effort scores in the NASA-TLX results.

It was also noticed that the tasks completion times were closely tied to individual factors, such as Braille literacy, age, and prior domain experience. In Task 1, P5, who was the only non-Braille reader, took considerably longer than others when navigating the file system TUI in icons mode. Relying primarily on the screen reader and occasionally struggling to distinguish between tactile shapes (e.g., U-shapes and circles), P5 suggested supplementing shapes with more semantically meaningful tactile symbols, such as “T” for text files. This indicates that non-Braille readers may require alternative representation strategies, however, it is difficult to generalize from this single case. In Task 3, P7, the oldest participant, required the most time and expressed a preference for having the settings menu presented in a tactile rather than purely audio format. The participant also frequently forgot button functions and later explained that he needed additional time to learn and memorize different functions. This suggests that tactile interfaces for older users may benefit from memory aids or multimodal reinforcement. Finally, in Tasks 2 and 4, P4 took the longest time, which may be explained by her professional familiarity with graphs, she appeared focused on extracting detailed information rather than completing the task as quickly as possible. Together, these cases illustrate that longer task times are not necessarily indicative of poor usability, but can instead reflect differences in literacy, sensory preferences, cognitive processing styles, and task interpretation. Designing with these variations in mind could improve inclusivity and efficiency across diverse user groups.

Additionally, the iterative evaluation process, followed in the evaluation, by collecting feedback and documenting challenges faced by users while interacting with the device, proved valuable in refining the interaction concepts implemented in the device. One area of significant improvement was the navigation mechanism for selecting the different files stored on the device. Feedback from the first three studies indicated that requiring users to manually highlight a file before opening it was not intuitive, as it introduced an unnecessary step. In response, and following a suggestion from P2, a default highlighting of the first file upon startup was implemented. This change improved the navigation and made the device more intuitive for subsequent participants, and reduced unnecessary time loss. Furthermore, the feedback mechanisms were refined to address challenges identified during the evaluation, such as adding distinct sounds for different buttons and menu navigation. These enhancements contributed to more seamless and intuitive interactions with the device.

The study also uncovered several opportunities for extending the functionality of 2D tactile displays. As many participants expressed interest in incorporating modern AI capabilities into the device such as allowing the user to select image and obtaining further explanation, an enhancement that would be especially valuable when interpreting complex images that cannot easily be conveyed through tactile feedback alone. Moreover, participants showed strong interest in expanding the device's capabilities beyond document viewing. P3 suggested that the device could support gaming, while P4 expressed a desire for internet connectivity to browse the web and access emails. This indicates a broader potential for the device to serve as a multi-functional tool, encompassing not only assistive technology but also entertainment and communication functionalities.

Additionally, the feedback on document editing capabilities revealed a need for more interactive features. Participants, particularly P2, emphasized the importance of being able to add comments and signatures to documents. This suggests that future versions of the device should incorporate such functionalities, making it more versatile for professional use.

The study also revealed the diverse needs and preferences of BLV users when it comes to interaction with the device. While two participant expressed a preference for having the settings menu in a tactile format, the rest of the participants indicated that audio-only navigation was sufficient. Furthermore, one participant mentioned that for her, audio navigation alone would suffice, as she primarily requires tactile feedback only for reading long text and interpreting graphics.

This variation in user needs underscores the importance of offering flexibility in the modalities used for interaction. Some users may prefer tactile feedback for detailed information such as text and graphics, while others may find audio feedback more efficient for navigation and accessing non-visual content. These differences highlight the necessity of designing devices that can adapt to individual preferences, ensuring that both tactile and audio feedback are seamlessly integrated to meet the diverse requirements of the user population. Future developments should therefore consider providing customizable options that allow users to choose between different modalities depending on their specific needs and tasks.

5.7 Conclusion

This chapter presented the design and development of a hi-fi prototype of a portable 2D tactile display. The prototype was informed by lo-fi designs created by participants who are BLV during earlier design workshops. By clustering the lo-fi designs based on the placement of device controls and the size of the tactile display, four design variants were identified. The design preferred by most participants, featuring the largest tactile display area, was selected for the hi-fi prototype.

To support portability and independent use, a new file system TUI was developed, allowing users to store, access, and interact with files directly on the device. The file manager included two distinct view modes, enabling tactile representation of files in either list or icon format. The chapter also described the hardware and enclosure design, which incorporates a Raspberry Pi 4, and introduced a GUI to support developers and sighted collaborators by providing a visual counterpart to the tactile display.

The prototype was evaluated in a formal user study with nine blind participants. Results showed that participants were able to successfully access and navigate files stored on the device, and they reported high levels of satisfaction with the overall experience. Thematic analysis of the data revealed five core categories, including suggestions for future improvements such as incorporating AI-based functionalities, enabling document editing, and supporting additional applications like web browsing and gaming.

6 Conclusion and Future Work

6.1 Conclusion

This chapter presents an overview of the key findings and contributions made in this dissertation and offers a perspective on potential future work.

The design of 2D tactile displays remains an evolving field, with no established standards for designing effective interaction concepts, hardware specifications, or software ecosystems. Unlike designing GUIs, where existing guidelines ensure consistency across devices and applications, 2D tactile displays lack a unified design framework, leading to fragmented development efforts and usability challenges. Current available displays often suffer from limited resolution, inconsistent tactile feedback, and restricted interaction methods, making them difficult to use efficiently for tasks, such as document exploration, graph interpretation. Furthermore, many tactile interfaces which are designed without sufficient user involvement, result in systems that do not fully align with the needs and expectations of individuals who are BLV.

To address these challenges, this dissertation set out to develop a structured approach for designing and prototyping 2D tactile displays, integrating both hardware and software solutions, and actively involving users who are BLV throughout the entire design process. The research was guided by three key objectives:

1. Establishing principles for TUIs design, by developing interaction concepts for representing and navigating complex digital content, such as documents and graphs commonly used in STEM fields (Chapter3).
2. Investigating design methods and focusing on strategies to actively engage participants who are BLV in the design process (Chapter 4).
3. Developing a functional 2D tactile display prototype that incorporates insights and feedback from users who are BLV, and evaluating the usability, effectiveness, and overall success of this design (Chapter 5).

To achieve these objectives, multiple user studies and design workshops were conducted with users who are BLV. At the time of this research, however, the final actuators (taxels) for the new 2D tactile display were not yet available, so an existing tactile display from Metec AG. [69] was used for prototyping and evaluation. Although this required certain adaptations, it did not impede the overall design process. On the contrary, it created an opportunity to focus on developing flexible and scalable software solutions, represented by the TUIs presented in Chapter 4, that can be adapted to future hardware implementations.

This dissertation makes the following key contributions to the field of 2D tactile display design, emphasizing the importance of both innovative interaction design and active involvement of users who are BLV throughout the process. The following section discusses the contributions of this dissertation in more detail.

Requirements for Designing Effective TUIs for 2D Tactile Displays.
The research presented in this dissertation analyzed different approaches for designing TUIs for effective representation and navigation of complex digital content, with a particular focus on documents and graphs relevant to STEM fields. The studies conducted with individuals who are BLV, as shown in Chapter 3 and 4 highlighted specific user needs and requirements for accessing STEM materials, such as complex documents and graphical information like diagrams through tactile means. Building on lessons learned from the literature review on designing interaction

concepts for 2D tactile displays in other contexts, this work introduced a novel approach that applies information visualization guidelines commonly used in GUIs. Specifically, Shneiderman's VISM [80] was employed to present tactile information across different view modes, which proved effective for presenting documents on 2D tactile displays. Crucially, early testing of these concepts with blind users using embossed or physical prototypes was shown to be highly valuable for creating meaningful and intuitive tactile interactions, allowing for rapid iteration and deeper insight into user needs before digital implementation.

Moreover, the chapter revealed that many users valued access to information in its original spatial format, such as diagrams, rather than relying solely on alternative text descriptions. However, user preferences varied in the case of representing documents on 2D tactile displays, where some prioritized experiencing the full document layout and spatial relationships, while others found accessing textual content to be sufficient. The work further demonstrated how modern intelligent solutions, including AI-based document analysis, could be leveraged to extract and present complex information, such as document layouts, in formats accessible via tactile displays. This integration of intelligent processing with well-designed navigation and interaction concepts represented a crucial step toward making STEM content more inclusive and accessible for users who are BLV.

Second, this research demonstrated how involving users who are BLV in the design and prototyping phases can significantly enhance both hardware and software development. By engaging participants through prototyping workshops and iterative feedback cycles, the study uncovered nuanced user needs that would likely be overlooked if end users were only involved during final evaluation stages. On the hardware side, the workshops emphasized that a one-size-fits-all approach does not adequately address the diverse needs of users who are BLV in 2D tactile displays. User characteristics such as age, experience, and background were found to strongly influence interaction preferences, which in turn shape design requirements. For example, users interested in gaming devices tended to design control elements resembling consoles or input combinations, while those focused on drawing devices preferred interaction concepts such as gestures or additional buttons. Age also played a crucial role: older users prioritized simplicity, predictability, and ease of locating controls. More experienced users often suggested advanced interaction features, including virtual keyboards and gesture support, highlighting the need for devices that can scale in complexity. In contrast to general-purpose devices, this research yielded a device design purpose-built specifically for STEM applications, addressing the unique challenges of navigating and interacting with complex, structured content.

How Can Users Who Are BLV Actively Contribute to the Design Process of Assistive Technologies?
Another key contribution of this work, presented in Chapter 4, is the development of a novel method that adapts existing lo-fi prototyping approaches to allow users who are BLV to actively and collaboratively design assistive technologies in pairs. The chapter highlighted the importance of adapting, not only the materials used in these workshops, but also the overall environment and workshop settings.

The method followed a two-phase process. In the first phase, users who are BLV were consulted to help design a lo-fi prototyping toolkit and refine the structure of the workshops. In the second phase, workshops were conducted with pairs of participants who are BLV, supported by a sighted moderator and two sighted assistants.

The findings from ten design workshops employing this approach highlighted several key considerations for successfully involving users who are BLV in the design process. Regarding the design of materials, it is important to build on previous research and collaboratively refine materials with participants, ensuring that complex software concepts are communicated clearly and understandably. The structure of the workshops should balance individual and collaborative prototyping, provide sufficient time for participants to explore the toolkit, and share the workshop agenda in advance. The workshop environment also plays a critical role: participants benefit from textual descriptions of tasks, seating arrangements that support collaboration, grouping based on individual needs, and attention to language barriers. Finally, the role of sighted assistants must be clearly defined to support participants without dominating the process. Assistants should be knowledgeable about the topic and focus on documenting design elements, such as notes, drawings, or photos, to aid participants' recall.

By incorporating these lessons, the workshops successfully positioned users who are BLV as active contributors and main designers, demonstrating that co-design approaches can be both accessible and inclusive. The chapter concluded with practical recommendations, derived from the workshop findings, aimed at improving the accessibility, structure, and facilitation of design workshops involving users who are BLV.

The Role of High-Fidelity Prototyping in 2D Tactile Display Design.
Finally, this dissertation highlighted the critical importance of employing hi-fi prototyping within the design lifecycle of 2D tactile displays. The hi-fi prototype developed in this work enabled realistic simulation of the tactile, auditory, and interactive qualities of the device, offering users a near-authentic experience of how the final system would operate. This level of fidelity was essential for collecting rich, detailed, and accurate feedback on usability, comfort, and overall interaction, which are insights that can be challenging to obtain from lo-fi prototypes or purely conceptual designs.

The hi-fi prototype also created a platform for participants to engage deeply with the device, explore its functionalities, and identify both strengths and areas for improvement. As a result, users were able to contribute numerous concrete suggestions for new features, interaction refinements, and accessibility enhancements, demonstrating that hi-fi prototyping is not only valuable for evaluation but also for fostering innovation. By bridging the gap between conceptual design and real-world use, the hi-fi prototype provided a foundation for informed design decisions and underscored the importance of iterative, user-centered approaches in developing assistive technologies for users who are BLV.

6.2 Future Work

Future work includes investigating how external applications can be integrated into the device, allowing users to load and utilize additional software tools. Furthermore, this research was conducted using a single display, the HyperBraille, as it was the only available device at the time. The HyperBraille display offers a relatively high refresh rate compared to other tactile displays available during this study. As future devices are expected to support higher refresh rates, it would be valuable to analyze how the designed TUIs perform on displays with lower refresh rates, such as Tactonom or DotPad. This would help assess potential usability challenges and inform design adaptations for broader compatibility.

Additionally, this dissertation primarily focused on representing documents and vector-based graphics. However, documents often contain images that cannot be represented as vector graphics, raising the need to explore optimized strategies for rendering such content on tactile displays. In this work, a simple thresholding algorithm was used to convert grayscale images into a binary tactile representation. While this approach is computationally efficient, it may not always preserve important structural details. Future research could investigate alternative computer vision techniques, such as edge detection algorithms to enhance contour representation, image segmentation methods to differentiate meaningful regions, or deep learning-based approaches to simplify and extract key features from complex images.

Building on the findings of this dissertation, several areas warrant further exploration to refine and expand the design of 2D tactile displays and their associated software ecosystem. The key directions for future work include:

Designing a Software Development Kit (SDK) for TUI Development: To promote broader adoption and innovation in applications for 2D tactile displays, the development of an SDK for such devices warrants further exploration. Such a toolkit would offer standardized components for building new TUIs, supporting consistency across different applications. The SDK could streamline the conversion of text and graphics into Braille and tactile formats, tailored to the resolution of the specific 2D tactile display in use.

Enhancing Collaboration Chances Between Sighted and Blind Users: Future development should explore additional features that support and enhance collaboration between sighted and blind users when working with 2D tactile displays. While this research introduced a GUI to enable sighted developers to interact with and test TUIs, further extensions of this GUI could allow for more dynamic, real-time collaboration. For instance, the GUI could be expanded with features such as shared annotations, live highlighting, or real-time cursor tracking could help both users maintain a shared understanding of the content and interaction context. Additionally, tools for co-editing or co-creating tactile layouts, where sighted users can contribute visual structuring and blind users provide feedback on tactile readability, could support inclusive workflows in educational, design, or workplace settings.

Conducting Extended User Studies: While this research focused on developing a co-designed hi-fi prototype, the final hardware for the tactile display was not yet available. Future work should integrate the developed software and interaction concepts into a finalized device, enabling long-term usability testing in real-world settings. Extended studies could examine daily use and workflow integration, assessing how users interact with the device in different contexts.

A Appendix

A.1 Low Fidelity Prototyping Phase 1 Scenario

A.1.1 Introduction and Overview - 25 Minutes

We aim to develop a new portable 2D refreshable tactile display featuring two example applications: a file explorer and a graphics viewer. The file explorer will present available files and folders as tactile symbols or icons arranged in a grid structure, while the graphics viewer will allow users to interact with visual data, including zooming and panning. Although some functionalities will be accessible via touch, all interactions will also be operable through physical buttons. To facilitate this, we are creating a low-fidelity prototyping method that allows blind users to design their own 2D tactile display prototypes. We have developed an initial toolkit comprising various elements that represent the buttons and control features of the tactile display, along with a magnetic board to simulate the device's interface. In this session, we invite your feedback on the toolkit and the prototyping method. Your insights will be invaluable in assessing the effectiveness of the toolkit and refining the prototyping process to better meet user needs. Our goal is to determine whether the toolkit is sufficient for creating functional and intuitive prototypes and to make improvements based on your experiences and suggestions. This interview will be audio recorded if this is fine for you?

We will start by some demographic question:

- How old are you?
- Visual impairment age?
- Education level?
- Have you ever been to a similar prototyping session before?

We defined as list of initial buttons and interactions for the new device, however,, you can add any other buttons you think are necessary:

- Cursor buttons (up, down, left, right, select) – 5 buttons. X
- Home - 1 button X
- Settings (Einstellungen) – 1 button
- Back – 1 button
- power – 1 button X
- volume (up and down) - 2 buttons X
- zoom (in and out) – 2 buttons
- Audio enable – 1 button
- Touch enable – 1 button

- USB port
- USB-C port or power pin
- Optional buttons:
- Braille keyboard – 8 buttons

A.1.2 Prototyping Session - 45 Minutes

Can you please explore the buttons and arrange them on the board to create your prototype. You can ask anytime if you need help or if something is not clear.

A.1.3 Feedback Session - 20 Minutes

- What do you think about the toolkit?
- Are the buttons easy to distinguish?
- Which of the materials did you prefer (wood, clay our 3d printed buttons)?
- Were there missing shapes or components that you were hoping to find?
- How easy was it for you to place the buttons and arrange them?
- Which height of buttons did you prefer?
- What changes would you suggest to improve the toolkit?
- What changes would you suggest to improve the prototyping method?
- Would you prefer to this prototyping method within a group or individually, each person gets his board and arranges it ?
- Other suggestions?

A.2 Low Fidelity Prototyping Phase 2 Scenario

A.2.1 Phase 1: Exploratory Workshop Feedback Questions

A.2.1.1 Questions on the toolkit

1. What do you think about the toolkit?
2. How easy was it to distinguish the buttons?
3. Did they prefer certain materials used in the workshop?
4. Did they miss any shapes or components?
5. How easy was it to place the buttons and arrange them?
6. Are there any recommendations for enhancing the toolkit?

A.2.1.2 Questions on the lo-fi prototyping method

1. Are there any suggestions for improving the prototyping process?
2. Are there any preference for individual versus group prototyping sessions?

A.2.2 Phase 2: Prototyping Workshop Scenario

A.2.2.1 Welcome and Overview (10 Minutes):

The aim of today's workshop is to design a 2-dimensional tactile display using a magnetic board and 3D printed material. The focus is on functionality and ergonomics. You will also discuss what features this new device should have. Here is a brief overview of what we are doing today:

1. In the first ten minutes I will give you an introduction about the available software that the future display will have and about the toolkit (i.e. the magnetic board and the printed material).
2. Then we will form two groups, each group consisting of a blind person and a sighted assistant. You will have 45 minutes to design your own prototype. During this time please explain your design ideas out loud to your assistant. If you have any difficulties or would like to discuss ideas, you are welcome to do so with your assistant. Assistants should not make suggestions unless explicitly asked.
3. Then we will have a collaborative design session, in which you will examine a second person's prototype, discuss your design decisions together and design a new device together.
4. Finally, we have a ten minutes wrap up and feedback session.

A.2.2.2 Introduction and Material Exploration (10 Minutes):

The new tactile display that you are designing today contains two sample applications: a file explorer that displays the available files and folders as symbols or icons in a grid structure and a graphics viewer. Each application offers different ways of interacting with the data. For example, in the graphics viewer you should be able to zoom and move a graphic. There are three embossed pages in front of you. The first two (smaller) pages show the graphics viewer and the file explorer. On the third page is the list of functions that are available in all applications. Feel free to add new functions as needed. Next to the embossed pages is a large magnetic board, which is the toolkit. On the magnetic board you will find all the materials you need to design the new tactile display:

1. At the top left of the magnetic board there are large square pieces that represent the tactile area of the display, i.e. the screen of the device. Alternatively, you can also use the embossed pages.
2. At the bottom left you will find magnetic strips that you can use as separators.
3. In the center of the magnetic board are various 3D-printed shapes that represent the buttons or other control elements. You will find a specific shape in each column (1st column circles, 2nd column smaller circles, 3rd column rectangles, 4th column ovals, 5th column squares, 6th column arrows, 7th column rectangles but a little higher, 8th column USB ports).
4. In the top right-hand corner of the panel, you will find clay that you can use if you need a specific button that you cannot find in the toolkit.
5. To the left of the toolkit board, there is a box with magnetic surfaces on all sides. This box represents the case of the 2D tactile display. You can arrange the buttons or other control elements on it as you wish.

A.2.2.3 Individual Design Session (45 Minutes) :

Now you can start designing the display. Feel free to ask your assistant for help if you need support.

A.2.2.4 Collaborative Design Session (30 Minutes) :

Now you can present your ideas to the other blind person and then design a tactile display together. Each of you has 5 minutes to explore the other person's prototype.

A.2.2.5 Evaluation and Feedback Session (20 Minutes):

1. Was the toolkit and materials enough to design your prototype?
2. How was your experience today?
3. How did you find the collaborative work?
4. Is there something you did not like or would like to improve?

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Sara Alzalabny

Embedded Systems Engineer

LANGUAGES

German - C1
English - C1 / TOEFL 104
Arabic - Native language
Spanish - A1

TECHNICAL SKILLS

- C++/ C
- Qt
- Python
- Eagle
- Fusion360
- LTSpice
- Matlab
- VHDL

PUBLICATIONS

- Designing a Tactile Document UI for 2D Refreshable Tactile Displays: Towards Accessible Document Layouts for Blind People – MDPI
- Touch for Accessibility: Haptic SVG Diagrams for Visually Impaired and Blind Individuals – IEEEHaptics
- ChartFormer: A large vision language model for converting chart images into tactile accessible SVGs – ICCHP
- Other Publications: https://orcid.org/0000-0002-3533-2473

HOBBIES

- Digital Art
- Amigurumi Design
- Pottery and Sculpture

WORK EXPERIENCE

08/2022 - today

Researcher and PhD Student

KIT - Karlsruhe Institute of Technology

- Development of a new 2D tactile display for blind and visually impaired in the field of accessible human-computer interaction
- Design and implementation of software architecture and the development of application software
- Design and development of hardware prototypes

06/2020 - 07/2022

Embedded Software Engineer

NewTec GmbH

- Development of software solutions for medical technology, covering requirements, testing, and documentation
- Creation of software design and architecture
- Firmware development for embedded systems

04/2019 - 05/2020

Master Student and HiWi

Fraunhofer IAF

- Development of a 100 GHz radar embedded Linux system
- Implementation and execution of DSP algorithms
- Development of a Linux driver for a QSPI device

04/2018 - 03/2019

Student Trainee

NewTec GmbH

- Firmware development for embedded systems

EDUCATION

04/2016 - 05/2020

Master - Embedded Systems

Albert Ludwig University of Freiburg

- Major Circuits and Systems, Reliable Embedded Systems

10/2015 - 06/2020

German Language Course

Clausthal University of Technology

- VHS German classes from B1 to C1

04/2009 - 09/2014

Bachelor - Electrical Engineering

Ain Shams University in Cairo

- Major Electronics and Communication Engineering

09/2006 - 04/2009

High School Certificate

Modern Schools Esmat in Cairo

CERTIFICATES

01/2014

Advanced Training Seminar at Vodafone

- Seminar on career preparation and acquisition of soft skills, with a focus on building effective teams

09/2013

Cisco CCNA Certified Network Associate

- Basic knowledge and skills in network technologies, including installation, configuration, and management of networks

08/2013 - 09/2013

Internship bei Orange S.A.

IT Network Administrator

- Installation, configuration, and management of networks

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