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Classification of 2D refreshable tactile user interfaces

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Abstract Assistive technologies for visually impaired people tend to map graphical and visual information into audio and tactile interactive representations. Within these, two-dimensional tactile devices are included and used mainly to represent graphic elements (data-sheets, tables, charts and, images) in interactive pin-matrix displays. The mapping process is rather challenging in user interface design since most assisted devices do not have the fundamental elements and necessary interactions to convey graphical information. Beyond that, several braille nomenclatures and interface designs can be used, not existing a standard classification and standard definitions of the most outstanding interactions and features that should be included in the development of these user interfaces. This paper presents a modernise analysis and classification on two-dimensional refreshable tactile user interfaces formed on hardware characteristics, outstanding interactions, user design challenges and domain coverage. Moreover, the set of challenges and obstacles in the development of these user interfaces as its characteristics are also presented.

Keywords 2D Refreshable Tactile User Interfaces · User Interface Classification · Visually Impaired Users · Assistive Technologies · Audio-Tactile Interaction

1 Introduction

The European Blind Union (EBU) and the World Health Organisation (WHO) estimate that 30 million persons in Europe are visually impaired, where 22.5 million are unemployed due to their sight loss, [1,2]. Beyond orientation and mobility problems, blind people also have to deal with information access normally and strongly presented in graphical and visual user interfaces on computers, graphics, text documents, mobile phones, and others. Visually impaired people cannot access these elements and information through the visual modality, being only able to do it using tactile and audio user interfaces.

Assistive technologies for visually impaired people were developed with the goal of improving the visually impaired person life's quality and information access. Single-line braille readers

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are a specific category of assistive technologies for blind people that focus on improving the visually impaired information access. Nonetheless, these are restricted to a single braille line, which cannot convey graphical and two-dimensional data, but only text information. Beyond audio descriptions, visually impaired people could not access graphical information intuitively and effectively since swell, and braille tactile graphics are not refreshable, which means that the user cannot change the graphic elements or have a more detailed description of a specific element. Two-dimensional charts, excel sheets, mathematics graphics, tables, diagrams and pictures are graphical elements that cannot be accessed using single-braille displays due to their complexibility and cannot be either accessed by swell and braille graphic papers since the information in these elements is often dynamic.

To surpass this obstacle, two-dimensional refreshable tactile devices and displays were born, providing not only textual information but dynamic graphical and two-dimensional information access. The refreshable characteristic allows users to access and interact with dynamic information and the two-dimensional displays allow users to experience two-dimensional graphics and pictures. A new door opened for visually impaired people since they could now have effective access to graphic information and graphic user interfaces used by sight people. The first state-of-the-art two-dimensional refreshable tactile display explicitly developed for visually impaired people was conceptualised by *Metec AG* in 1985 and entitled as the *Dot Matrix Display (DMD) 120060*. Since then, several 2D Refreshable tactile user interfaces were developed for several objectives, orientation and mobility tasks since they convey memorisation and construction of cognitive maps, [3], educational systems, text, graphics and 3D models reading, interactive models and entertainment.

Designing efficient, interactive and easy to use user interfaces is important to help society or a particular culture realise the potential benefits of these technologies and how to use them. Poor user interface designs usually result in higher training costs and increased error rates, demotivating users to use the product, [4]. User interface design is one of the most difficult challenges in the development o 2D refreshable tactile displays since the information needs to be mapped and structured to a new form, with interactive features and intuitive elements, [5], using only tactile and audio modalities, [6]. Nonetheless, the user interfaces conceptualisation, especially for these devices, involves several challenges and obstacles to surpass since visually impaired people interaction is different from sighted people. Several two-dimensional tactile user interfaces have been developed. However, the user interface design standards for these devices are not yet established. This paper aims to contribute and present which two-dimensional refreshable tactile user interfaces have the most remarkable and most intuitive features for visually impaired user interaction and what should be the preferred standard characteristics for these user interfaces.

Surveys on refreshable graphic tactile displays for visually impaired people were developed in [7], [8]. In [7], a more general haptic and tactile user interfaces comparison was made. Nonetheless, a focused hardware analysis on *METEC AG* refreshable tactile displays only was created, where parameters as pin-distance, dimensions, weight, and pin-matrix mechanism were evaluated. Moreover, in [8], the displays were classified in two groups, *static* and *dynamic* displays. Static refreshable displays are used when the fingers explore the contours of the screen, whereas dynamic displays consist of a pointer device with a small tactile display attached. It is important to clarify that the focus of this survey was on mechanical and hardware aspects of these devices, while our focus was mainly on user interface and human-machine interaction. We did approach a hardware classification since input and output should be included as the technology's user interface. However, we did not distinguish between static refreshable devices and dynamic refreshable devices. In this overview and user interface classification, we considered only static refreshable devices, where the user uses his hand to explore all the display. We did not include dynamic refreshable devices in this classification, considering that these devices have reduced display size and that single-line braille displays are not two-dimensional. Further explanation regarding this topic is addressed in section 3.

Beyond mechanical and hardware characteristics, our user interface classification is based on human-machine interactions. Remarkable and outstanding interaction features, functionalities and domains were used as the classification criteria. Our classification was focused on the user interfaces used in assistive technology for visually impaired people since they focus only on tactile and audio interactions to convey information. We evaluated the user interface at several levels, hardware characteristics, obstacle surpassing (drawbacks), outstanding interactions, and domain coverage to further foment our analysis and conclusions. The main goal of this paper was to define the fundamental requirements for this type of user interface, present the central challenges and obstacles in user interface design, and analyse and classify the most remarkable user interfaces.

In short, the contributions of the paper are:

- The definition and set of requirements for two-dimensional refreshable tactile displays.
- The main challenges and obstacles in the conceptualisation and development of 2D refreshable tactile user interfaces.
- An hardware, software, domain coverage and feature analysis on two-dimensional refreshable tactile user interfaces.

The remainder of this paper is structured as follows: Section 2 presents a background on user interface and tactile interaction in assistive technology. Section 3 defines the set of requirements for two-dimensional refreshable tactile user interfaces and presents the most notorious developed user interfaces of this type by describing the noteworthy characteristics and drawbacks. Section 4 presents a list of the most challenging obstacles in developing two-dimensional refreshable tactile user interfaces. Section 5 concerns to the user interface classification and discussion. Section 6 presents the main conclusions and global analysis on these user interfaces and future work proposal.

2 Background

Tow-dimensional refreshable tactile feedback and user interfaces are mainly used in assistive technology for visually impaired people. In order to conceptualise and define the limit of two-dimensional refreshable tactile user interfaces, it is crucial to define and address the terms *User Interface* and *Tactile Interaction*. In this chapter, we are going to address these terms to be able to select the set of characteristics that should be considered in our user interface analysis and are important for user interaction.

2.1 User Interface

Tow-dimensional refreshable tactile feedback and user interfaces are mainly used in assistive technology for visually impaired people. In order to conceptualise and define the limit of two dimensional refreshable tactile user interfaces, it is crucial to define and address the terms *User Interface* and *Tactile Interaction*. In this chapter, we will address these terms to select the set of characteristics that should be considered in our user interface analysis and are important for user interaction.

The user interface can be interpreted as having direct and indirect paths, [9]. Direct paths involve all physical elements and ways of signal transfer between human-machine while indirect paths involve the signal organisation according to internal models that are shared by the human and the machine. The user interface is seen as the point of human-computer interaction and communication in a device, hence being included in the concept of human-computer interaction (*HCI*) in [10]. This can include display screens, keyboards, mouses and other hardware components. According to [11], the user interface is not necessarily constituted by artificial physical elements. The physical elements can be replaced by the user's own hands, proving that physical elements are not requirements in user interfaces. Bødker in [12], makes the analogy of user interface with a new pair of glasses, which we use to reveal new angles and details to us and enhance our curiosity to seek several answers to different types of questions.

Our user interface definition was based on *Bødker*'s definition, [12], where technological innovations, both concerning hardware/software and design methods, are included as the user interface design. This definition was used for this specific user interface classification and analysis since both parts have an important role in user interaction. The user interaction in a large display of braille dots where he can use both hands to touch the tactile interface will be different in a smaller display where only one hand at the time can explore the interface (different hardware). User interaction is also different for a pin-matrix device that uses pinpoint audio descriptions and does not use audio (different software) despite having the same hardware characteristics. We consider as part of the user interface all the input and output physical equipment of the device, as well as the software layer responsible for the human-computer interaction. We also established that devices that are considered to have more than one user interface due to having two sources of output information (audio and haptic) should have their user interfaces analysed as one whole user interfaces for a more concise analysis UI classification. If we had considered two or more user interfaces for the same device, we would not evaluate and distinguish each device's user interface fairly.

2.2 Tactile

It is essential to establish the difference between haptic and tactile user interfaces since both terms are commonly used in assistive technologies research for blind people, and no difference is stated between haptic and tactile in most dictionary definitions, [13]. The word *haptic* refers to the sense of touch, being this sense twofold, including cutaneous or tactile touch and kinesthetic touch, [14].

Kinesthetic information refers to all the information acquired through the sensors in the joints, muscles and tendons, including position, velocity and forces of one's body state. Tactile information refers to the information acquired through sensors in the skin, including pressure, texture, puncture, thermal properties, softness, wetness, friction-induced phenomena, adhesion, shape, edges and embossing features, [15,16]. According to [17], the tactile aspect refers to the information received from the nerve terminals of the skin, while the kinesthetic refers to the dynamic aspects of said interaction with the object.

Tactile interaction design in 2D tactile refreshable user interfaces is often developed in conjunction with audio interactions and audio feedback (audio tones, earcons, auditory icons, speech and 3d sound), [18]. Considering that the majority of these user interfaces use audio feedback, they can be classified as multimodal user interfaces or, more specifically, in 2D refreshable audio-tactile user interfaces. It is widely recognised that multimodal user interfaces have the potential to be more intuitive and improve the human-computer interaction when carefully implemented and design, opening doors for accessible computer interfaces and technologies for the visually impaired, [19,20]. Audio only feedback is ineffective in noisy environments, while haptic only feedback becomes ineffective in bumpy environments. If the information is provided both in audio and haptic format, the message is more reliably received, and the environmental constraints can be solved, [21,22,23].

3 Requirements and Characteristics

For two-dimensional refreshable tactile displays, different nomenclatures and terminologies can be used, two-dimensional pin-matrix devices, dynamic pin display, two-dimensional braille displays, two-dimensional touch-sensitive pin matrix, refreshable planar haptic display and, full-page braille display. In this section, it is going to be analysed all the devices included in the aforementioned nomenclatures. It is going to be presented the list of requirements and specifications for this type of user interfaces in order to define the user interface limits of this type. This is necessary for the reason that there is not a substantial definition of two-dimensional refreshable tactile user interfaces. In addition, there is not a vast set of developed 2D refreshable pin-array devices. However, the specification presented is based not only on our own characteristic analysis but also on a related list of requirements presented in [24].

3.1 UI Requirements

The pins must proportionate an acceptable and ample touch/force resistance since visually impaired users have different ways to read Braille and tactile graphics. Some people might exert a light touch force while others may have a heavier fingertip reading touch. To reach and include all users, the system must assure good uniformity in the raised pins with hard end-edged stops mechanism.

The distinguishing characteristic between single-line and two-dimensional refreshable braille displays is the planar pin-array dimension. The pin-array must be two-dimensional, to be able to represent graphical information. Single-line braille displays are constituted by four rows, three for the braille character representation and one for the current keyboard position. These refreshable tactile displays were not considered two-dimensional since they cannot represent graphic information with just four rows.

Dynamic tactile displays were also not included in this classification and user interface overview since these do not reproduce friction forces (frictionless), which are intuitive and essential in pin-matrix tactile interactions for visually impaired, [8,25,26]. One example of a dynamic tactile display is the remarkable reading aid, OPTACOM, [27], developed in 1966. These devices do also have reduced display size, which is another drawback since they cannot present complex graphic information. Friction forces are generated when fingers explore a relief, in this case, a pin-matrix device. Therefore these forces are a requirement in two-dimensional refreshable tactile displays.

Initially, we did not cover multi-line braille displays since there is no equally spacing between rows in the graphic display (no equidistant pins), meaning that not all types of two-dimensional graphic information could be represented. However, we opted to include them since they are two-dimensional (have more than four rows) and can still represent a substantial part of two-dimensional graphical information, [28,29,30].

The refreshable time rate is crucial for two-dimensional refreshable tactile user interfaces. The system needs to be able to update the tactile information in real-time to be used for visually impaired people.

Lastly, the technology must provide a noticeable difference between a raised pin and a non-raised pin. This difference should be perceptible to any user. In [24], it is proposed that a non-raised pin should be positioned at least 0.025 mm below the reading surface, and a raised pin should raise between 0.06 and 0.09 mm above the surface, [31].

3.2 UI Description

With the user interface characteristics and specifications for two-dimensional refreshable tactile displays established, a research for these devices was made in the scientific field and in the market field. In the scientific field, our research overview was based on the Google Scholar platform using the nomenclatures aforementioned for two-dimensional refreshable tactile user interfaces. We also included the devices of this type referred in related work surveys, [8,7]. In the market field, we use information from international trade fairs for aids for the visually impaired, as the *SightCity* fair in Frankfurt, Germany. This research was done with the purpose of including all the most outstanding 2D refreshable user interfaces to further contribute to a complete overview and classification. It was necessary to use different name nomenclatures since not all devices and companies use the same name.

In this section, we are going to present an overview of 2D refreshable tactile devices respective user interfaces characteristics since there is the need to point out the unique features and interactions of each user interface for further analysis and a complete classification. The overview was not only chronologically organised but author, company and project-based structured. We assume that one two-dimensional refreshable tactile display device has one global user interface associated in other to compare both hardware and software characteristics as a whole. The conferred description does not include all the details of the devices but only remarkable characteristics and features. Further characteristics and details are presented and compared in section 5.

[A] HyperBraille project and *metec AG*.

It is hardly possible to do an overview of 2D refreshable tactile displays without mentioning the HyperBraille project, being considered the state-of-the-art in the development of this kind of devices and user interfaces, [32]. The end-goal of this project was to increase visually impaired people job opportunities by providing modern graphical user interfaces. The main challenge of this project was to convert the contents of graphical desktop applications to a tactile graphic representation in a display with only 120×60 pins. The *HyperBraille* system together with *metec Ingenieur-AG*, [33] developed several pin-matrix device with the *HyperBraille software* [34]. We included the most relevant developed user interfaces and tactile displays from this project.

A.1 DMD 120060 UI in 1985, [35].
The first static multi-modal 2D refreshable tactile user interface was concealed by *metec AG* in 1985. This user interface was the first to combine refreshable pin arrays feedback with audio interaction. The user uses a sensor ring for finger recognition. The sensor has eight dots of precision and returns the centre position.

Fig. 1: DMD 120060 from metec AG

A.2 BrailleDis 9000 UI in 2008, [18].
This user interface was developed to map window-based user interfaces into tactile interactive information. The tactile information displayed in the two-dimensional display is split into four regions (header, body, structure and detail), [36]. The header zone is responsible for presenting the statues, and main properties and the body region is used to present the main application content, occupying roughly 58.0 % of the display screen. To highlight the current position and similar operations, the structure zone is used, occupying the left or right side of the screen display. The detail region is used to present all the details of the focused element. The BrailleDis 9000's user interface is also capable of input gesture, using the braille cells touch sensors to locate finger and hand pressure points, [37,38], including multi-touch input gesture, [39]. Different domains applications were developed, entertainment (gaming), [40], graphics creation (SVG) and drawing, [41] and *orientation & mobility* aids, [42], [43]. More complex user interface interactions were also developed, such as multi-view windowing technique and other window operations, [44,45], drag and drop interaction was concealed in [46], and blinking pins for points of interest in [42].

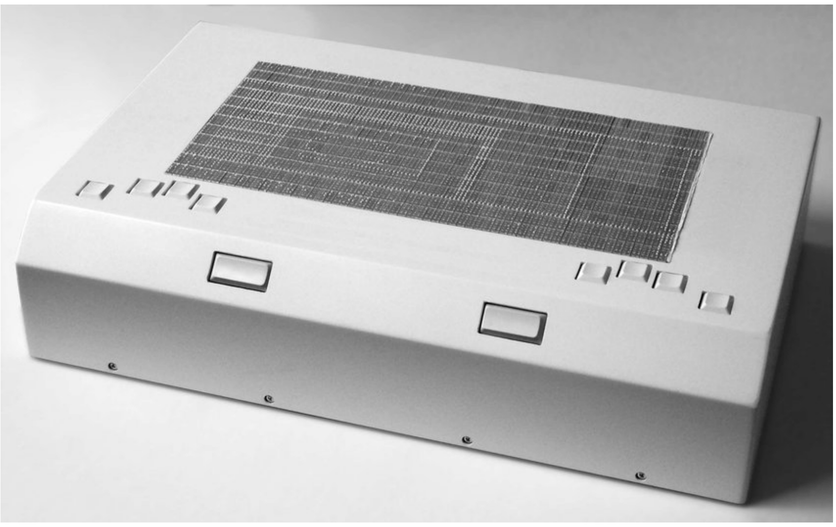

Fig. 2: BrailleDis 9000 from metec AG

A.3 Metec Portable Pin-matrix display UI in 2012, [47].
A tactile display user interface for 3D obstacle detection and tactile representation of maps was developed in 2012, [47,48]. This refreshable pin-array device has an array of 30×32 pins (slightly smaller than the others HyperBraille pin-arrays) and has no buttons attached. The user interacts with the system using s Wii remote with buttons for panning and zooming operations.

Fig. 3: Metec Portable Pin-matrix display from metec AG

A.4 BrailleDis 7200 UI in 2014, [49].
In 2014, a new version of the BrailleDis display from *metec AG* was redesigned and presented. T The new device differences are in input controls, keyboard positioning and input functionalities. Mouse wheels, cursor keys, gesture keys and a navigation bar were added in other to work independently from a external keyboard. The *Tangram* workstation was developed to improve graphic edition and creation using the *OpenOffice Draw*, [50]. It was also developed a framework that provides structure consistency for the development of two-dimensional tactile applications, namely *BrailleIO*, in [51]. Education domain applications were developed in [52] and new complex user interface components as the focus zoom in [53].The goal of this functionality is to assure that the focused element does not vanished from the tactile area after the zoom operation.

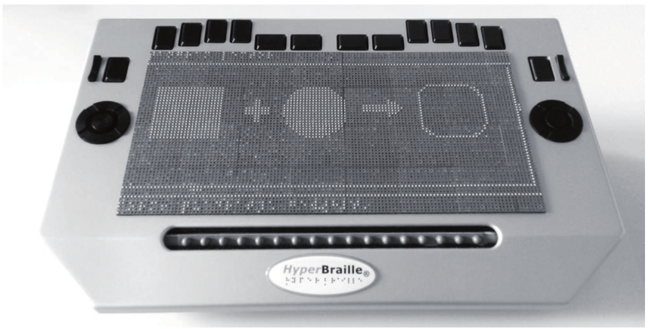

Fig. 4: BrailleDis 7200 from metec AG

[B] *KGS Corporation*

B.1 Dot View Point diagram DV-1 UI in 2002. *KGS Corporation* developed their first tactile graphic display. This display had 768 dots, arrow keys, buttons and a 4-way lever key. It was designed as a computer operation support tool but could be used as a figure learning tool (mapping figures to tactile) and as a learning tool for ink characters.

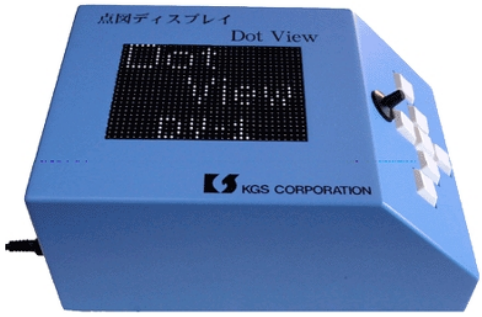

Fig. 5: Dot View Point diagram DV-1 from KGS Corporation

B.2 Dot View Point diagram DV-2 UI in 2003.
One year later, the device suffered an improvement in dots resolution (higher number of dots), increased number of multi-purpose function buttons, and became slightly lighter. The remaining functions and interfaces did not suffer a substantial modification. These devices can also perform click simulation and drag operations in images and braille reading.

Fig. 6: Dot View Point diagram DV-2 from KGS Corporation

[C] *Handy Tech GmbH*

C.1 The Maple-GWP-System UI in 2006, [54].
A Braille display system for visually impaired students to create and explore mathematical graphics without assistance was developed by *Handy Tech GmbH* in 2006. Several user interface functions are supported by this device, such as zooming, navigation, different types of representation ("dot mode" and "line mode"), highlighted pin (blinking pin), select objects and orientation mode.

Fig. 7: The Maple-GWP-System from Handy Tech GmbH

[D] *National Institute of Standards and Technology - NIST*

D.1 NIST Tactile graphic display UI in 2007, [55].
In 2002, the National Institute of Standards and Technology started to develop a two-dimensional tactile graphic display. The designed prototype has a reading surface mounted on an X-Y graphics plotter, where standard plotter language is used to write images. Education systems, engineering design, web surfing and image viewer are the functionalities implemented in this device. The pin-array refresh rate depends on the image complexity (five seconds to a minute). The user control interface was designed and evaluated by collaborating with the National Federation of the Blind (NFB).

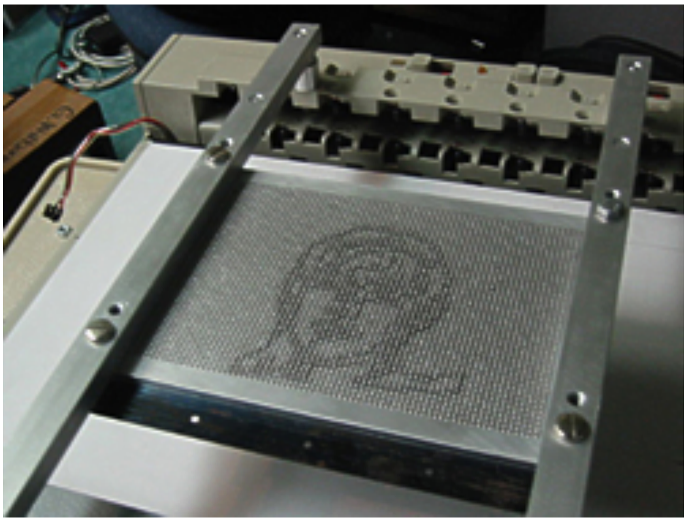

Fig. 8: NIST Tactile graphic display from the National Institute of Standards and Technology - NIST

[E] *Tactisplay Corp*

E.1 TACTIS 100 UI in 2015, [29].
A 100-cell multi-line braille screen reader was developed by *Tactisplay Corp* in 2015. It's constituted by four lines of 25 braille cells, equipped with navigation buttons and navigation guidelines. Nonetheless, it does not supports graphic representation. We decided to include it since it is a multi-line braille display that can be compared with other multi-line displays present in this paper.

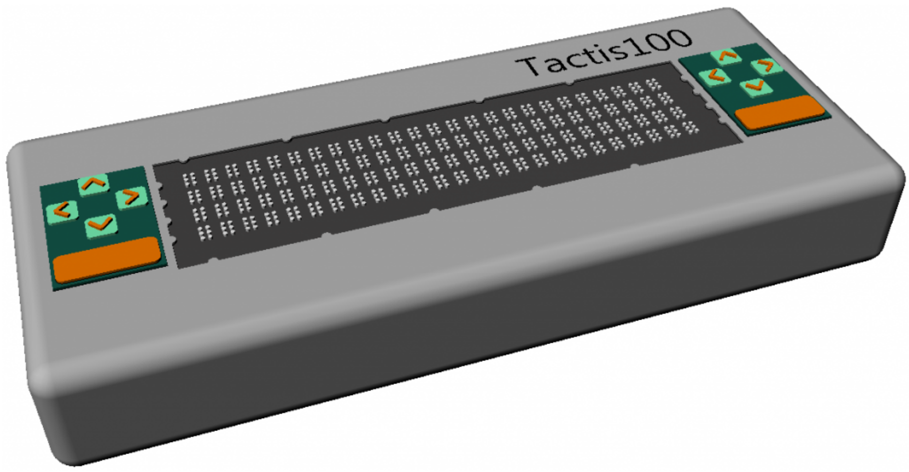

Fig. 9: TACTIS 100 from Tactisplay Corp

E.2 TACTIS Table UI in 2015, [56].
From the same company, a graphical view refreshable tactile display was developed in 2015. Mathematical equations, tables, images, graphs and related graphical content can be displayed in this user interface. It has the capacity of displaying 1000 braille cells with a total of 12000 tactile pixels, making it the largest refreshable tactile display at the moment.

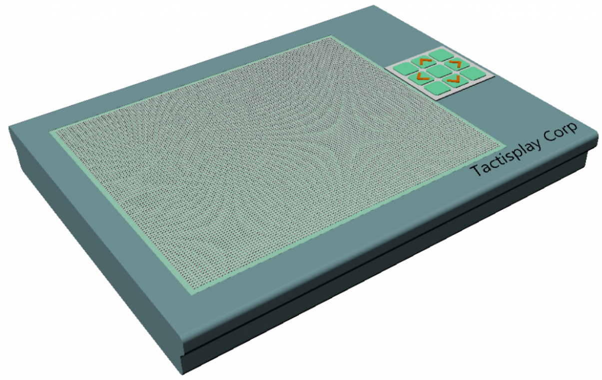

Fig. 10: TACTIS Table from Tactisplay Corp

E.3 TACTIS Walk UI in 2015, [57].
A two-dimensional refreshable tactile display that maps a USB camera image to tactile representation was named TACTIS Walk. The remarkable feature of this user interface is the image process from the input image to the output binary image. The product was designed to be used while walking.

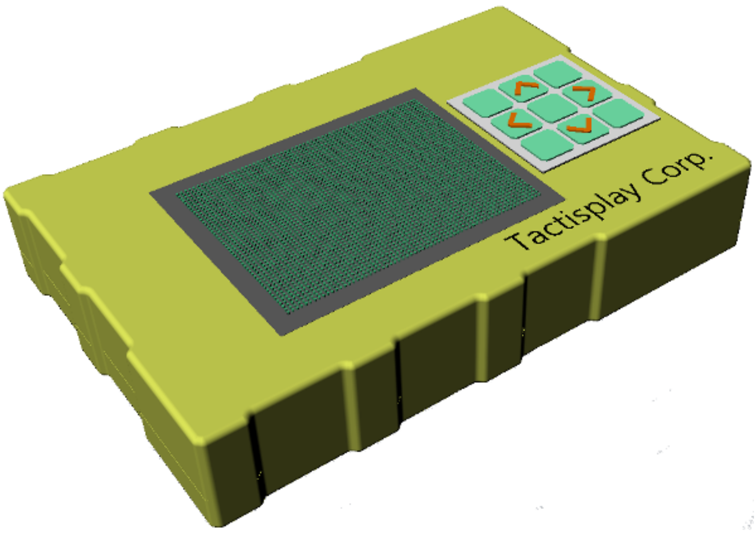

Fig. 11: TACTIS Walk from Tactisplay Corp

[F] *BLITAB Technology GmbH*

F.1 BLITAB UI in 2016, [30].
A multi-line braille refreshable tactile tablet was developed by BLITAB Technology GmbH entitled “BLITAB, iPad for the blind”, [58]. It is composed of 14 braille lines, volume control buttons and a rear camera. Web page conversion, book reading and entertainment applications are all included, supporting USB pen support as well. Despite the scarce technical information, this UI was included in this classification.

Fig. 12: BLITAB from BLITAB Technology GmbH

[G] *Dot Incorporation*

G.1 Dot Pad (Prototype) UI in 2017, [59].
The Dot Pad is described as a multi-layered braille display with 300 braille cells (8 dots each). It has been under development, and it’s expected to come out in the market in early 2022. Its purpose is to convey images, graphics, and charts to the visually impaired. Despite the fact that there is barely any information and data about this product user interface, we decided to include all its available and data.

Fig. 13: Dot Pad from Dot Incorporation

[H] *BlindPAD Project*

H.1 BlindPad UI in 2017, [60].
A personal assistive device (PAD) for visually impaired people started to be developed in 2014. This system was constituted by three major components, a two-dimensional refreshable tactile display with 192 moving pins, graphic-to-tactile mapping software and rehabilitation orientation exercises for the blind. The focus domain of this project was in educational applications and in orientation and mobility skills learning for blind people at school age. The main disadvantage is the dot spacing and dot diameter size being 8 mm and 4 mm, respectively, which makes it impossible to use Braille. The justification for this decision was the use of LEGO bricks for map representation and spatial knowledge learning. The tactile display pins were designed with the same spacing of LEGO dots (8 mm) for a more concise and clear orientation learning process, [61].

Fig. 14: BlindPad from BlindPAD Project

[I] *Inventivio GmbH*

I.1 Tactonom (Prototype) UI in 2017, [62].
The first prototype of *Tactonom* was presented by *Inventivio GmbH* in 2017. It has 10591 tactile pins, being the largest display among all two-dimensional refreshable tactile devices. This user interface is used mainly as a computer GUI replacement with tactile and audio modalities. Nevertheless, it also includes other domains and functionalities such as orientation, education quizzes and gaming. Despite not having the touch-sensitive ability, it does finger recognition by using a built-in camera, which opens doors to several other functionalities related to computer vision. The major drawback is the pin refreshment rate, being only at 0.05Hz.

Fig. 15: Tactonom from Inventivio GmbH

[J] *Bristol Braille Technology CIC*

J.1 CANUTE 360 UI in 2019, [28].
Despite being commercially released in 2019, Canute 360 is a project with more than six years of development of a multi-line refreshable braille display. The user interface (built-in Python) is open-source, empowering expansion and user improvement. The Canute 360 is composed by nine braille lines where the pins are not either equidistant between lines and between braille cells. It supports several domains as book reading, music, maths, tabular data and abstracted tactile graphics and, it is not computer dependable (portable), using an SD-Card port for file reading instead.

Fig. 16: CANUTE 360 from Bristol Braille Technology CIC

[K] *Orbit Research*

K.1 Graphiti UI in 2020, [63].
Another computer in-dependable (portable) refreshable tactile display was released in 2020. Despite not using audio feedback for the user interface, it provides the ability to set each pin to different heights (multi-level) with the goal to convey a third dimension of information which can be used to convey colour information in tactile images and graphs. The focus of this user interface is on educational and entertainment programs (drawing). The major drawback is the oversized space between the pins in the pin-array matrix, which is too big to represent braille characters (4mm).

Fig. 17: Graphiti from Orbit Research

4 Challenges and main obstacles

In this chapter, we are going to describe the main obstacles and challenges that 2D refreshable tactile user interfaces have to face and solve in their user interface design to evaluate further the user interface resilience on these challenges.

The proposed list was conceptualised based on related work analysis, [5], [34], [64], from challenge (a) to challenge (f). The remaining challenges are based on our own breakdown and analysis based on the presented user interface flaws and disadvantages of the studied devices. The solutions conferred by the several user interfaces are further addressed and compared later in this document, section 5.

(a) Display exploration loss. When the user loses track in the 2D refreshable tactile display due to using other tactile input interaction than the pin-matrix array (Tactile Buttons, navigation bar, cursor keys, mouse wheel). Important and most-used functions should avoid hand movements over a long distance.

(b) Midas touch effect. When the visually impaired user accidentally triggers a non-desirable function by activating an input functionally while exploring the pin-matrix. The blind user should not feel hesitant or unconfident when using the refreshable tactile device.

(c) Usable refreshable rate. The refreshable information must be updated at a real-time refreshment rate so the system can be interactive and usable. Since the *DMD 120060* represents the state-of-the-art for two-dimensional refreshable tactile user interfaces, the system's refreshment rate should be bigger than 0.05 Hz.

(d) Braille compatibility. Two-dimensional refreshable tactile devices are designed to represent graphical information, but nevertheless, not all displays are able to represent braille information due to the spacing size between dots in the reading surface. According to the Braille Authority of North America code-books and guidelines, [31], the distance between two dots in the same cell should be higher than 2.3 mm and lower than 2.5 mm.

(e) Graphics compatibility. For graphic representation, the space between each pin and each line should be equidistant. Otherwise, it will constrain the number of graphics that can be represented.

(f) Information overload - It is necessary to avoid information overload when visual mapping media to tactile and audio haptic modalities since tactile displays resolution is smaller than regular screens. The tactile screen size must be sufficient to represent the mapped tactile information.

(g) Quick accessible information - Frequently accessed and needed information should be presented in a different way, where the user could easily access it and use it. Shortcuts should be implemented in the system in the form of buttons or other hardware interfaces.

(h) Sighted-compatible layout - Provide information with the same layout and form (or as similar as possible) as sighted people use it while preserving all the capabilities of the application. The goal is to improve and facilitate the interaction between visually impaired and sighted persons.

(i) Independence to external components - The system must ensure that all functionalities can be executed and used without the need to use any external input or output components as keyboards, mouses or earphones.

(j) Injury-free design - Edges should be avoided or rounded to reduce and minimise the risk of injury for visually impaired users. If the system contains risky elements, blind users will feel insecure and will not use the system at its maximum.

(k) Orientation loss in zooming - In large tactile displays, zooming is not as perceptible as for visually impaired people as it is for sighted people. If the blind user's reference point vanish from the visible area after the zoom operation, the user will not be able to understand the information.

(l) Internationalisation - The system might work just for a specific group of persons, but there are several braille languages, and within the same language, it can have different nomenclatures, as short-forms of words. (The word *and* is short-formed to n in some braille nomenclatures).

(m) Audio integration - It is challenging to use both audio and tactile interactions to convey information effectively in both channels. Which part of graphic information should be converted to audio and which part should be converted to tactile. Beyond text-to-speech elements, audio should improve the user interface orientation and interaction, with earcons and auditory tones feedback.

5 User interface Classification

Related work on the classification of refreshable tactile displays was already developed in [8]. However, this survey focus was on hardware components only. Therefore technologies after 2007 were not included in the survey. Nevertheless, our user interface classification focused on both hardware and software components as defined in section 3, including user interfaces from 1985 to 2020. Since the user interface is not just the software component or just the hardware component but everything that is related to the human-machine interaction, it can be classified at several levels. We are going to divide the user interface classification in 4 categories, hardware specifications, challenges and solutions coverage, interactions and remarkable features and, domain and function coverage to be able to present and provide a more complete conclusion. Each category is going to be presented and discussed in the next sub-sections.

5.1 Hardware specifications analysis

We compared the hardware characteristics of two-dimensional refreshable tactile user interfaces using a set of specifications and parameters. Each refreshable device was seen as part of a user interface, which means that the device is included in the whole user interface. The display size in centimetres and the total number of taxels (pins) was analysed. The horizontal spacing between the pins and the weight of the whole device was also taken into consideration. The pin refreshment rate of each display is also presented in Hertz, (frequency(Hz) = 1 / refreshment time(s)). The device's grounding-type can either be an independent system (works as a whole system) or dependent on other devices (computers and other external hardware components) like the traditional single-line braille readers. Lastly, we analysed the remarkable and exceptional hardware features. Table 1 represents the comparison of the aforementioned hardware characteristics.

In terms of the number of taxels and display size, *TACTIS Table* and *Tactonom* systems have the advantage of providing more detailed and complex tactile graphics. The most effective way to get the largest amount of detail and complexibility in a tactile figure is to increase and use a large display size, [55]. However, there is a substantial drawback in the pin-matrix refreshable rate, having both devices a refreshable rate inferior to 0.2 Hz, which is very slow compared to faster tactile displays refreshable rate, as the *BrailleDis 7200* (20 Hz) and the *KGS DV1* (20 Hz). The spacing size between taxels does not substantially fluctuate, with the exception of *BlindPAD* and *Graphiti* devices which cannot present Braille characters as a result of having distant taxels that can not provide the necessary tactile feedback for braille reading. The majority of refreshable two-dimensional tactile displays are dependable on external devices. The exemption are *BrailleDis 7200*, *Canute 360*, *Graphiti* and *BLITAB* which have their own computer integrated. *Tactonom* is the only two-dimensional refreshable tactile display that uses a camera for finger recognition and other computer vision approaches. *Portable Metec* and *TACTIS Walk* do have a camera integrated, but it is used as the input of an obstacle detection or image tactile mapping process, which does not correlate with user interfaces.

Table 1: Hardware user interface characteristics analysis. The size of the display is presented in centimetres and in number of taxels (pixel equivalent in pin-array displays). The spacing between each pin is expressed in millimetres and the total device weight in kilograms. The refreshment of the entire screen content is presented in Hz (R.Rate). It is also presented the device grounding and remarkable features of the hardware.

	Size		Spacing	Weight	R.Rate		Remarkable	
User Interface	(taxels)	(cm)	(mm)	(kg)	(Hz)	Ground.	Hardware	Year
(A.1) DMD 120060	7200	18.0 × 36.0	3.0	20	0.05	dep.	Ring sensor	1985
(A.2) BrailleDis 9000	7200	15.0 × 30.0	2.5	8	4.5	dep.	Touch S. [α]	2008
(A.3) Portable Metec	960	7.5 × 8.0	2.5	0.6	5	dep.	Wii [β]	2012
(A.4) BrailleDis 7200	7200	15.0 × 30.0	2.5	5.5	20	Indep.	F. Zoom [c]	2014
(B.1) KGS DV1	768	7.2 × 9.6	3.0	2.2	20	dep.	-	2002
(B.2) KGS DV2	1536	7.7 × 11.5	2.4	1.5	> 1	dep.	-	2003
(C.1) Maple-GWP	384	4.8 × 7.2	3.0	-	-	dep.	-	2006
(D.1) NIST Display	3621	12.7 × 17.8	2.54	-	0.03	dep.	X-Y Pos.	2007
(E.1) TACTIS 100	600	100 cells [d]	2.5	1.0	0.2	dep.	M. Braille	2015
(E.2) TACTIS Table	12000	25.0 × 30.0	2.5	6.0	0.125	dep.	Display Size	2015
(E.3) TACTIS Walk	2400	10.0 × 15.0	2.5	2.5	0.125	dep.	Camera	2015
(F.1) BLITAB	2520	420 cells [e]	-	-	-	Indep.	Airflow [f]	2015
(G.1) Dot Pad	2400	10.0 × 15.0	2.5	-	0.1	dep.	-	2017
(H.1) BlindPAD	192	12.8 × 9.6	8.0	-	0.52	dep.	LEGO size	2017
(I.1) Tactonom	10591	22.3 × 29.8	2.5	9.6	0.05	dep.	Camera	2017
(J.1) Canute 360	2160	$9 \cdot (6.2 \times 25.6)$ [g]	2.5	2.8	0.1	Indep.	M. Braille [h]	2019
(K.1) Graphiti	2400	16.4 × 24.6	4.1	1.8	0.2	Indep.	Multi level	2020

[α] Touch sensitive display surface.
[β] WiiCane (remote controller) for input interactions.
[c] Focus zoom functionality.
[d] 100 Braille cells (25 cells × 4 lines)
[e] 420 Braille cells (30 cells × 14 lines)
[f] Airflow channel based braille dots
[g] 9 braille lines of 25.6 × 6.2 cm
[h] Multi-line Braille display

Beyond the principal characteristics and hardware specifications, we made a comparison on input and output hardware characteristics of each pin-array device since there is a noticeable difference between each device. This comparison is presented in table 2.

Table 2: In-output hardware user interface analysis. (For input, it was considered buttons, navigation bar, gestures and finger position detection. For output, we analysed the use of text-to-speech and other sounds. The touch sensitive capability was also taken into consideration.) In the events with insufficient information, we assumed that the UI does not have the hardware characteristics (✓/✗).

	Input				Audio-Output		Touch
User Interface	buttons	nav. bar	gestures	finger pos.	TTS	sound	Sensitive
(A.1) DMD 120060	✗	✗	✗	✓	✗	✓	✓
(A.2) BrailleDis 9000	✓	✗	✓	✓	✓	✓	✓
(A.3) Portable Metec	✗	✗	✓	✓	✓	✗	✓
(A.4) BrailleDis 7200	✓	✓	✓	✓	✓	✓	✓
(B.1) KGS DV1	✓	✗	✗	✗	✗	✗	✗
(B.2) KGS DV2	✓	✗	✗	✗	✗	✗	✗
(C.1) Maple-GWP	✓	✗	✗	✗	✗	✗	✗
(D.1) NIST Display	✓	✗	✗	✗	✗	✗	✗
(E.1) TACTIS 100	✓	✗	✗	✗	✗	✗	✗
(E.2) TACTIS Display	✓	✗	✗	✗	✗	✗	✗
(E.3) TACTIS Walk	✓	✗	✗	✗	✗	✗	✗
(F.1) BLITAB	✓	✗	✓	✗	✓	✓	✗
(G.1) Dot Pad	✓	✗	✗	✗	✗	✗	✗
(H.1) BlindPAD	✗	✗	✗	✗	✓	✗	✗
(I.1) Tactonom	✓	✗	✗	✓	✓	✓	✗
(J.1) Canute 360	✓	✗	✗	✗	✓	✓	✗
(K.1) Graphiti	✓	✗	✓	✓	✗	✗	✓

In terms of user interface input and output interaction hardware characteristics, we can conclude that buttons are almost mandatory in the user interface design for these devices. The navigation bar implemented in *BrailleDis 7200* is unique, and according to the user's analysis on the system, [49], it is intuitive and usable for panning operations. Gesture and finger position recognition are not so common on these type of devices, however as expected, they improve user interface interaction, [39]. Audio is indispensable for visually impaired people. Therefore two-dimensional refreshable audio-tactile user interfaces have the upper hand, with both tactile and audio feedback available for user interaction.

5.2 UI Challenges and Solutions coverage analysis

Our software analysis on user interface elements is slightly different from the previous analysis since we do not have access to this kind of information in a substantial part of the compared user interfaces. We analysed which challenges and problems (described in chapter 4) are the user interfaces able to solve, based on the available information regarding the user interface design. It is important to refer that a green check-mark implies that either the user interface can solve the challenge or has positive characteristics, which means that it is a positive aspect of the user interface design. The results of this analysis are presented in table 3.

Table 3: User interface challenges analysis. The challenges were presented and described in section 4. Green check-marks (✓) indicates that the user interface design solves the challenge, and red cross (✗) either indicates that the UI does not solve the challenge or that there is no sufficient information to conclude.

User Interface	2D Refreshable user interface challenges												
	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)
(A.1) DMD 120060	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗
(A.2) BrailleDis 9000	✗	✗	✓	✓	✓	✓	✓	✗	✗	✓	✗	✗	✗
(A.3) Portable Metec	✓	✓	✓	✓	✓	✗	✗	✓	✗	✓	✗	✗	✗
(A.4) BrailleDis 7200	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗
(B.1) KGS DV1	✗	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	✗	✗
(B.2) KGS DV2	✗	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	✗	✗
(C.1) Maple-GWP	✗	✗	✗	✓	✓	✗	✓	✓	✗	✓	✗	✗	✗
(D.1) NIST Display	✓	✓	✗	✓	✓	✗	✗	✓	✗	✗	✗	✗	✗
(E.1) TACTIS 100	✗	✓	✓	✓	✗	✗	✗	✗	✗	✓	✗	✗	✗
(E.2) TACTIS Table	✗	✓	✓	✓	✓	✓	✗	✓	✗	✓	✗	✗	✗
(E.3) TACTIS Walk	✗	✓	✓	✓	✓	✗	✗	✓	✗	✓	✗	✗	✗
(F.1) BLITAB	✗	✗	✗	✓	✗	✗	✓	✓	✓	✓	✗	✗	✓
(G.1) Dot Pad	✗	✗	✓	✓	✓	✗	✓	✓	✗	✓	✗	✗	✗
(H.1) BlindPAD	✓	✓	✓	✗	✓	✗	✗	✓	✗	✓	✗	✓	✗
(I.1) Tactonom	✓	✓	✓	✓	✓	✓	✗	✓	✗	✓	✗	✓	✓
(J.1) Canute 360	✗	✓	✓	✓	✗	✓	✗	✗	✓	✓	✗	✓	✓
(K.1) Graphiti	✗	✗	✓	✗	✓	✓	✗	✓	✓	✓	✗	✗	✗

Display exploration loss is a rather common challenge in these user interfaces. Only user interfaces that do not use buttons. Hence, the user does not need to move his hand away from the tactile display or have a small tactile area are able to surpass this challenge. Another solution to solve this obstacle is to use audio navigation auxiliaries as guidelines as the *Tactonom* system uses. Beyond this challenge, information overload, independence to external components, orientation loss in zooming, system internationalisation, and audio integration are very challenging and intuitive user interface designs. Region-based approaches are used to deal with information overload, as the *BrailleDis* devices and the *Tactonom* use. The *BrailleDis 7200* user interface is the only one that solves orientation loss in zooming by using a focus element zooming technique. Audio integration is only achieved by three devices that use earcons and audio tones to improve the navigation and user interaction. The *NIST* and *DMD 120060* devices are the only ones that can slightly damage the user due to their user interface design with sharped edges and pins.

5.3 UI Interactions and remarkable features analysis

To further analyse the software component of two-dimensional refreshable user interfaces, a comparison of remarkable features and interactions used in each user interface was made. Interactive operations were analysed, such as tapping (click or double click in the display), panning (move current view), zooming (zoom in or out the view), rotating (rotate the view) and undo (reverse the last action). Element oriented operations were also taken into consideration, if the user can read the element content, whether it is selectable and highlighted (blinking pins) and if the user can modify the state of an application program (routing) as changing a tactile graph or an excel sheet. Multi-touch or multi-hand gesture support was also evaluated. Lastly, we analysed finger detection and gesture detection. Regarding finger detection and recognition, if true, we considered the finger recognition precision. Table 4 presents the aforementioned comparison.

Table 4: User interface features and remarkable interactions comparison. In the events with no available information regarding the user interface interactive operations and element operations, we assumed that the UI does not have those specific interactions (✗/✓) .

	Interactive operations					Element opera.			Multi-touch	Finger
User Interface	tap	panning	zoom	rotate	undo	read	routing	highlight	support	detect.
(A.1) DMD 120060	✓	✗	✗	✗	✗	✗	✗	✗	✗	8 dots
(A.2) BrailleDis 9000	✓	✓	✓	✗	✓	✓	✓	✓	✓	cell
(A.3) Portable Metec	✓	✓	✓	✗	✗	✓	✗	✗	✗	cell
(A.4) BrailleDis 7200	✓	✓	✓	✓	✓	✓	✓	✓	✓	cell
(B.1) KGS DV1	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗
(B.2) KGS DV2	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗
(C.1) Maple-GWP	✓	✓	✓	✗	✗	✗	✗	✓	✗	✗
(D.1) NIST Display	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
(E.1) TACTIS 100	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗
(E.2) TACTIS Table	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗
(E.3) TACTIS Walk	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
(F.1) BLITAB	✓	✓	✓	✗	✗	✓	✗	✗	✗	✗
(G.1) Dot Pad	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗
(H.1) BlindPAD	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
(I.1) Tactonom	✓	✓	✓	✗	✗	✓	✓	✓	✗	pin
(J.1) Canute 360	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗
(K.1) Graphiti	✓	✓	✓	✗	✗	✓	✗	✓	✓	pin

Regarding user interface features and interactions, tapping, panning and zooming are the most common interactions. Rotation interaction is only achieved by *BrailleDis 7200* in the drawing figures application. Undo operation is also only achieved by this device and its ancestor, *BrailleDis 9000*. Element operations as reading, routing and highlighting are only merely supported by the *BrailleDis* user interfaces and the *Tactonom* user interface. Routing implies a change in the state of an application program in the tactile graphic, which does imply a substantial level of intuitiveness. Multi-touch gesture interaction is only supported by the *BrailleDis* user interfaces and *Graphiti* user interface. The most precise finger detection method is used by the *Graphiti* and *Tactonom* devices, which support detection at the pin level.

5.4 UI domain and functions coverage

Lastly, we analysed the user interface domain and main functionalities. Based on the two-dimensional refreshable tactile display presented we were able to divided the user interface functionalities in six functions, Text Reader, Graph viewer, Orientation & Mobility, Education oriented, Entertainment applications. The user interface was also classified as a simple-function system or operating system based (multi functionalities and menu-driven) based on the previous parameters and the followings. If the system interface has a set of similar functionalities as a command line or graphical computer user interface, it is classified as operating system based UI. Examples of these functionalities are menu-driven user interface, web browsing functionality and, system options configuration. In other words, the system behaves like an operating system.

Beyond this classification, we have analysed the region and spatial arrangement of each pin-matrix user interface, how the available space region is segmented since this arrangement conveys consistency for visually impaired people. A user interface that simply maps an image or graph directly using the entire pin-matrix display does not have an innovative region arrangement. On the other hand, a user interface that uses specific pin-matrix areas for distinct functions and functionalities is a Region-based user interface. If the information is pre-processed and segmented in different regions of the pin-matrix display, the user interface is considered consistent and intuitive.

Table 5: Domain and functionalities comparison of 2d refreshable user interfaces. It is analysed whereas the user interface is capable of text reading, graph viewer, orientation and mobility applications, educational systems, entertainment applications(Gaming and Drawing). The user interface was classified based on domain (simple-function or Operating system based) and based on region arrangement (✓/ ✗). In the events of insufficient data, the symbol (✗) was used.

	UI Functions					Domain	Region
User Interface	Text r.	Graph v.	O&M	Education	Entertainment	class.	Arange
(A.1) DMD 120060	-	✓	✗	✗	✗	simple-func	✗
(A.2) BrailleDis 9000	✓	✓	✓	✗	✓	OS based	✓
(A.3) Portable Metec	✗	✗	✓	✗	✗	simple-func	✗
(A.4) BrailleDis 7200	✓	✓	✓	✓	✓	OS based	✓
(B.1) KGS DV1	✗	✓	✗	✗	✗	simple-func	✗
(B.2) KGS DV2	✗	✓	✗	✗	✗	simple-func	✗
(C.1) Maple-GWP	✗	✓	✗	✓	✗	simple-func	✗
(D.1) NIST Display	✗	✓	✗	✓	✗	simple-func	✗
(E.1) TACTIS 100	✓	✗	✗	✗	✗	simple-func	✗
(E.2) TACTIS Table	✓	✓	✗	✓	✗	simple-func	✗
(E.3) TACTIS Walk	✗	✗	✗	✗	✓	simple-func	✗
(F.1) BLITAB	✓	✗	✗	✓	✓	OS based	✗
(G.1) Dot Pad	✓	✓	✗	✓	✓	simple-func	✗
(H.1) BlindPAD	✗	✓	✓	✓	✗	simple-func	✗
(I.1) Tactonom	✓	✓	✓	✓	✓	OS based	✓
(J.1) Canute 360	✓	✗	✗	✓	✓	OS based	✗
(K.1) Graphiti	✗	✓	✗	✓	✓	simple-func	✗

The most common user interface function is a graphic viewer, as expected since two-dimensional refreshable tactile displays allowed graphic and image representations, which is not possible with single-line braille displays. The only user interfaces that do not support graphics view are the multi-line braille displays and the user interfaces that are used for image representation only (*Portable Metec* and *TACTIS Walk*). for obstacle avoidance and entertainment purposes, respectively. The *BrailleDis 7200* and the *Tactonom* are the exclusive devices that approach all of the presented user interface functionalities. One important factor is the domain classification that evaluates the system in terms of menu-driven interaction and operating system functionalities (change the status of elements and applications, undo operations, and others). The spatial-arrangement user interface is rather challenging in terms of user design, but it does provide an interactive and concise user experience. The blind person can use the region separations to acquire knowledge and data of the current application elements. It has constant feedback of the current application by using a menu-name region, and it can attain more details on a select element by using a detail region separation. These region-based interfaces are exclusively use in the *Tactonom* and *BrailleDis* user interfaces.

6 Conclusion

An analysis on two-dimensional refreshable tactile user interfaces, including not only the hardware components and characteristics but also the software elements and remarkable interactions, was developed in this paper. For a complete user interface overview and classification, we took into account the main challenges and obstacles of these displays, the intuitive interactions and features and the function domain where the user interface is inserted. The classification conceived on this paper was not merely on a single level or context but a multi-level classification, where the user interface was classified in terms of hardware characteristics, overcome obstacles and challenges, innovative features, domain classification and spatial arrangement.

Two-dimensional tactile user interfaces can help the user to distinguish if the text information derives from a regular text box or a description of a user interface element (widgets). This would not be possible in a single-line braille display, where the user would have to use context to conclude where does the information originate from. The main advantage is certainly the access to graphical and two-dimensional images. However, there are some user interfaces that convey information better and more intuitively than the others. Large display areas, high refreshment rates and the most usable spacing size between pins are hardware characteristics of outstanding two-dimensional refreshable tactile user interfaces. The use of audio and sound elements should not be forgotten since it can improve user interaction and increase the complexibility of the tactile graphics represented in these devices without information overload. Software user-intuitive and innovative interactions such as zooming, panning, element reading, system routing, element highlight and multi-touch support can be achieved and used in these devices. We also conclude that operating system based and region arrangement based user interfaces stand out since the user can benefit from these user interface designs by improving his general user experience and system usability as the *BrailleDis* devices and the *Tactonom* user interface provide.

It is important to mention that device costs were not taken into consideration since we focused on a user interface analysis. However, two-dimensional refreshable tactile displays are still far from the public market since they are not accessible and affordable to visually impaired people. We did not also include two-dimensional refreshable tactile devices with very reduced screen size since it goes against the principle of these user interfaces in presenting graphical and two-dimensional information which cannot be represented in a very limited size display.

For future work, we will work on the development of two-dimensional refreshable tactile user interfaces intuitive interactions in the *Tactonom* device from *Inventivio GmbH.* Beyond tactile interactions, we intend to use sound and audio feedback since it is not commonly used in this kind of user interfaces but can improve the general user interaction. It is also planned to do an overview on audio-tactile user interfaces used in assistive technology for visually impaired people, focused on an application domain classification.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

1. "World Health Organisation (WHO)." https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment. Accessed: 2021-03.
2. "European Blind Union (EBU)." http://www.euroblind.org/. Accessed: 2021-03.
3. L. Brayda, F. Leo, C. Baccelliere, C. Vigini, and E. Cocchi, "A refreshable tactile display effectively supports cognitive mapping followed by orientation and mobility tasks: A comparative multi-modal study involving blind and low-vision participants," in Proceedings of the 2nd Workshop on Multimedia for Accessible Human Computer Interfaces, MAHCI '19, (New York, NY, USA), p. 9–15, Association for Computing Machinery, 2019.
4. S. K. Card, The psychology of human-computer interaction. Crc Press, 2018.
5. S. O'Modhrain, N. Giudice, J. Gardner, and G. Legge, "Designing media for visually-impaired users of refreshable touch displays: Possibilities and pitfalls," IEEE transactions on haptics, vol. 8, 08 2015.
6. H. Thimbleby, A. Blandford, P. Cairns, P. Curzon, and M. Jones, "User interface design as systems design," in People and Computers XVI - Memorable Yet Invisible (X. Faulkner, J. Finlay, and F. Détienne, eds.), (London), pp. 281–301, Springer London, 2002.
7. D. Prescher, "Taktile interaktion auf flächigen brailledisplays," 2016.
8. F. Vidal-Verdú and M. Hafez, "Graphical tactile displays for visually-impaired people," IEEE transactions on neural systems and rehabilitation engineering : a publication of the IEEE Engineering in Medicine and Biology Society, vol. 15, pp. 119–30, 04 2007.
9. W. B. T. A. Furness, Virtual environments and advanced interface design. Oxford University Press on Demand, 1995.
10. F. Churchville, "User interface (ui)," 2019.
11. P. Pulli and P. Antoniac, "User interface," 2004. US Patent 6,771,294.
12. S. Bødker, "Through the interface - a human activity approach to user interface design," DAIMI Report Series, vol. 16, Apr. 1987.
13. "Merriam-webster online dictionary." https://www.merriam-webster.com/. Accessed: 2021-02-09.
14. M. O'Malley and A. Gupta, Haptic Interfaces, pp. 25–73. Elsevier Science, 12 2008.
15. K. Salisbury, F. Conti, and F. Barbagli, "Haptic rendering: introductory concepts," IEEE Computer Graphics and Applications, vol. 24, no. 2, pp. 24–32, 2004.
16. V. Hayward, O. Ashley, C. Hernandez, D. Grant, and G. Robles-De-La-Torre, "Haptic interfaces and devices," Sensor Review, vol. 24, pp. 16–29, 03 2004.
17. J. Carter and D. Fourney, "Research based tactile and haptic interaction guidelines," Guidelines on Tactile and Haptic Interaction (GOTHI 2005), pp. 84–92, 01 2005.
18. T. Völkel, G. Weber, and U. Baumann, "Tactile graphics revised: The novel brailledis 9000 pin-matrix device with multitouch input," in Computers Helping People with Special Needs (K. Miesenberger, J. Klaus, W. Zagler, and A. Karshmer, eds.), (Berlin, Heidelberg), pp. 835–842, Springer Berlin Heidelberg, 2008.
19. M.-L. Bourguet, An Overview of Multimodal Interaction Techniques and Applications, pp. 95–101. IGI Global, 2009.
20. Y. Bellik and D. Burger, "Multimodal interfaces: New solutions to the problem of computer accessibility for the blind," in Conference Companion on Human Factors in Computing Systems, CHI '94, (New York, NY, USA), p. 267–268, Association for Computing Machinery, 1994.
21. E. Hoggan, A. Crossan, S. A. Brewster, and T. Kaaresoja, "Audio or tactile feedback: Which modality when?," in Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI '09, (New York, NY, USA), p. 2253–2256, Association for Computing Machinery, 2009.
22. A. Pirhonen and K. Tuuri, "In search for an integrated design basis for audio and haptics," in Haptic and Audio Interaction Design (A. Pirhonen and S. Brewster, eds.), (Berlin, Heidelberg), pp. 81–90, Springer Berlin Heidelberg, 2008.
23. A. Karpov and R. Yusupov, "Multimodal interfaces of human–computer interaction," Herald of the Russian Academy of Sciences, vol. 88, pp. 67–74, 01 2018.
24. N. H. Runyan and D. B. Blazie, "The continuing quest for the 'Holy Braille' of tactile displays," in Nano-Opto-Mechanical Systems (NOMS) (J. Esteve, E. M. Terentjev, and E. M. Campo, eds.), vol. 8107, pp. 87 – 103, International Society for Optics and Photonics, SPIE, 2011.
25. M. Shimojo, M. Shinohara, and Y. Fukui, "Human shape recognition performance for 3d tactile display," IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans, vol. 29, no. 6, pp. 637–644, 1999.
26. G. Moy, U. Singh, E. Tan, and R. Fearing, "Human psychophysics for teletaction system design," The Electronic Journal of Haptics Research, vol. 1, 03 2000.
27. J. G. Linvill and J. C. Bliss, "A direct translation reading aid for the blind," Proceedings of the IEEE, vol. 54, no. 1, pp. 40–51, 1966.
28. "CANUTE 360 - Bristol Braille Technology CIC." http://bristolbraille.co.uk/index.htm. Accessed: 2021-03.

29. "TACTIS 100 - Tactisplay Corp." http://www.tactisplay.com/tactis-100-2/. Accessed: 2021-03.
30. "BLITAB - BLITAB Technology GmbH." http://blitab.com/. Accessed: 2021-03.
31. "Unified English Braille Formats and Guidelines - Braille Authority of North America." http://brailleauthority.org/formats/formats2016.html. Accessed: 2021-03.
32. "HyperBraille project." http://hyperbraille.de/. Accessed: 2021-03.
33. "Metec Ingenieur-AG." https://www.metec-ag.de/. Accessed: 2021-03.
34. D. Bornschein, J. Bornschein, W. Köhlmann, and G. Weber, "Touching graphical applications: bimanual tactile interaction on the hyperbraille pin-matrix display," Universal Access in the Information Society, vol. 17, 06 2018.
35. C. Power, "On the accuracy of tactile displays," in Computers Helping People with Special Needs (K. Miesenberger, J. Klaus, W. L. Zagler, and A. I. Karshmer, eds.), (Berlin, Heidelberg), pp. 1155–1162, Springer Berlin Heidelberg, 2006.
36. M. Schiewe, W. Köhlmann, O. Nadig, and G. Weber, "What you feel is what you get: Mapping guis on planar tactile displays," in Universal Access in Human-Computer Interaction. Intelligent and Ubiquitous Interaction Environments (C. Stephanidis, ed.), (Berlin, Heidelberg), pp. 564–573, Springer Berlin Heidelberg, 2009.
37. I. Sturm, M. Schiewe, W. Köhlmann, and H. Jürgensen, "Communicating through gestures without visual feedback," in Proceedings of the 2nd International Conference on PErvasive Technologies Related to Assistive Environments, PETRA '09, (New York, NY, USA), Association for Computing Machinery, 2009.
38. M. Schmidt and G. Weber, "Multitouch haptic interaction," in Universal Access in Human-Computer Interaction. Intelligent and Ubiquitous Interaction Environments (C. Stephanidis, ed.), (Berlin, Heidelberg), pp. 574–582, Springer Berlin Heidelberg, 2009.
39. M. Schmidt and G. Weber, "Enhancing single touch gesture classifiers to multitouch support," in Computers Helping People with Special Needs (K. Miesenberger, J. Klaus, W. Zagler, and A. Karshmer, eds.), (Berlin, Heidelberg), pp. 490–497, Springer Berlin Heidelberg, 2010.
40. R. Gutschmidt, M. Schiewe, F. Zinke, and H. Jürgensen, "Haptic emulation of games: Haptic sudoku for the blind," in Proceedings of the 3rd International Conference on PErvasive Technologies Related to Assistive Environments, PETRA '10, (New York, NY, USA), Association for Computing Machinery, 2010.
41. C. Taras and T. Ertl, "Interaction with colored graphical representations on braille devices," in Universal Access in Human-Computer Interaction. Addressing Diversity (C. Stephanidis, ed.), (Berlin, Heidelberg), pp. 164–173, Springer Berlin Heidelberg, 2009.
42. L. Zeng and G. Weber, "Audio-haptic browser for a geographical information system," in Computers Helping People with Special Needs (K. Miesenberger, J. Klaus, W. Zagler, and A. Karshmer, eds.), (Berlin, Heidelberg), pp. 466–473, Springer Berlin Heidelberg, 2010.
43. L. Zeng, "Non-visual 2d representation of obstacles," SIGACCESS Access. Comput., p. 49–54, Jan. 2012.
44. C. Taras, M. Raschke, T. Schlegel, T. Ertl, D. Prescher, and G. Weber, "Improving screen magnification using the hyperbraille multiview windowing technique," in Computers Helping People with Special Needs (K. Miesenberger, J. Klaus, W. Zagler, and A. Karshmer, eds.), (Berlin, Heidelberg), pp. 506–512, Springer Berlin Heidelberg, 2010.
45. D. Prescher, G. Weber, and M. Spindler, "A tactile windowing system for blind users," in Proceedings of the 12th International ACM SIGACCESS Conference on Computers and Accessibility, ASSETS '10, (New York, NY, USA), p. 91–98, Association for Computing Machinery, 2010.
46. M. Spindler, M. Kraus, and G. Weber, "A graphical tactile screen-explorer," in Computers Helping People with Special Needs (K. Miesenberger, J. Klaus, W. Zagler, and A. Karshmer, eds.), (Berlin, Heidelberg), pp. 474–481, Springer Berlin Heidelberg, 2010.
47. L. Zeng and G. Weber, "3dod: A haptic 3d obstacle detector for the blind," in Mensch & Computer 2012 – Workshopband: interaktiv informiert – allgegenwärtig und allumfassend!? (H. Reiterer and O. Deussen, eds.), (München), pp. 485–488, Oldenbourg Verlag, 2012.
48. L. Zeng, G. Weber, and U. Baumann, "Audio-haptic you-are-here maps on a mobile touch-enabled pin-matrix display," in 2012 IEEE International Workshop on Haptic Audio Visual Environments and Games (HAVE 2012) Proceedings, pp. 95–100, 2012.
49. D. Prescher, "Redesigning input controls of a touch-sensitive pin-matrix device," in TacTT@ITS, 2014.
50. J. Bornschein and D. Bornschein, "Collaborative tactile graphic workstation for touch-sensitive pin-matrix devices," in TacTT@ITS, 11 2014.
51. J. Bornschein, "Brailleio - a tactile display abstraction framework," in TacTT@ITS, 11 2014.
52. W. Köhlmann and U. Lucke, "Alternative concepts for accessible virtual classrooms for blind users," in 2015 IEEE 15th International Conference on Advanced Learning Technologies, pp. 413–417, 2015.
53. D. Prescher and G. Weber, "Comparing two approaches of tactile zooming on a large pin-matrix device," in Human-Computer Interaction - INTERACT 2017 (R. Bernhaupt, G. Dalvi, A. Joshi, D. K. Balkrishan, J. O'Neill, and M. Winckler, eds.), (Cham), pp. 173–186, Springer International Publishing, 2017.
54. P. Albert, "Math class: An application for dynamic tactile graphics," in Computers Helping People with Special Needs (K. Miesenberger, J. Klaus, W. L. Zagler, and A. I. Karshmer, eds.), (Berlin, Heidelberg), pp. 1118–1121, Springer Berlin Heidelberg, 2006.

55. J. Roberts, O. Slattery, J. O'Doherty, and T. Comstock, "37.2: A new refreshable tactile graphic display technology for the blind and visually impaired," SID Symposium Digest of Technical Papers, vol. 34, no. 1, pp. 1148–1151, 2003.
56. "TACTIS Table - Tactisplay Corp." http://www.tactisplay.com/tactis-table-2/. Accessed: 2021-03.
57. "TACTIS Walk - Tactisplay Corp." http://www.tactisplay.com/tactis-walk-2/. Accessed: 2021-03.
58. C. Hayes, "Electronics lend a helping hand to young and old," Engineering Technology, vol. 12, no. 1, pp. 40–41, 2017.
59. "Dot Pad - Dot Incorporation." https://dotincorp.com/. Accessed: 2021-03.
60. "BlindPAD Project." https://www.blindpad.eu/. Accessed: 2021-03.
61. L. Brayda, F. Leo, C. Baccelliere, E. Ferrari, and C. Vigini, "Updated tactile feedback with a pin array matrix helps blind people to reduce self-location errors," Micromachines, vol. 9, no. 7, 2018.
62. "Tactonom (The Tactile Graphics Display) - Inventivio GmbH." https://www.tactonom.com/tactile-graphics-display/. Accessed: 2021-03.
63. "Graphiti - Orbit Research." https://www.orbitresearch.com/product/graphiti/. Accessed: 2021-03.
64. W. Köhlmann, F. Zinke, M. Schiewe, and H. Jürgensen, "User-interface filter for two-dimensional haptic interaction," in Computers Helping People with Special Needs (K. Miesenberger, J. Klaus, W. Zagler, and A. Karshmer, eds.), (Berlin, Heidelberg), pp. 498–505, Springer Berlin Heidelberg, 2010.