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A REVIEW AND COMPARATIVE ANALYSIS OF REFRESHABLE BRAILLE DISPLAYS

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Abstract

The refreshable Braille devices stand at the frontier of digital accessibility for the blind and visually challenged, where both actuator hardware and software architecture jointly define their true performance, usability, and affordability. On the hardware front, this review dissects actuator mechanisms such as piezoelectric, electromagnetic, and shape memory alloys, by highlighting their operational principles, response characteristics, and lifecycle modelling. Six of the world-wide leading commercial devices (Orbit Reader 20, Braille Note Touch Plus, Braille Star 80, Dot Pad, Seika series, and Actilino 3.0) are benchmarked against key engineering metrics, with an emphasis on back-end control electronics such as MOSFET-driven switching networks. Complementing this hardware overview, the software component is also analysed through the lens of operating systems, accessibility APIs, Braille translation algorithms, and real-time dot rendering mechanism. A novel optimization method, Differential Dot Configuration (DDC), is introduced to reduce energy consumption and mechanical wear and tear during Braille transitions. The review further highlights underexplored aspects such as tactile hardware ergonomics, software-hardware co-design, and adaptive frameworks for evolving inclusive technology. By consolidating insights across control systems, algorithms, and assistive ergonomics, this work showcases a comprehensive roadmap for future Braille technologies that are affordable, adaptive, and inclusive by design.

Keywords:

Braille, Actuators, Assistive Technology, Artificial Intelligence, Natural Language Processing

1. INTRODUCTION

Currently in India, it is estimated that there are about 4.95 million blind people and over 70 million vision-impaired persons, out of which 0.24 million are blind children [1]. To empower these individuals to become the most active contributors to the society, they must have access to both printed and digital information. Louis, who was blinded at the age of three, invented the Braille system in 1824 while being a student at the Institution Nationale des Jeunes Aveugles (National Institute for Blind Children), Paris. "Braille", a universally accepted system of writing and reading used by blind persons. The Braille script consists of 63 characters, each formed by six raised dots arranged in a specific positional matrix within a Braille cell. These Braille characters (as shown in Fig.1) are imprinted on paper as individual lines and the codes are read by passing the fingers gently over the script [2].

Braille remains a cornerstone in accessible literacy for the visually impaired. Traditional methods of teaching Braille require continuous handholding from an educator who is specialized for individuals with special needs. But, there is a shortage of these specialized tutors for the visually impaired (QTVIs) in India, which leads to an insufficient supply to meet the demand for improving Braille literacy. This literacy rate is only 1% at the national level, and the global average is at ~10% [3]. With the growth of digital platforms, refreshable Braille devices/displays offer an interactive means to bridge traditional tactile reading with modern electronic interfaces which are ergonomically designed. Braille is key to developing literacy skills among people who are blind [45]. By providing a strong foundation for education, personal growth, and employment through its accessibility in skilling. While audiobooks and screen readers grant access to information, they cannot teach the fundamental rules of spelling, grammar, punctuation, and sentence structure, etc.

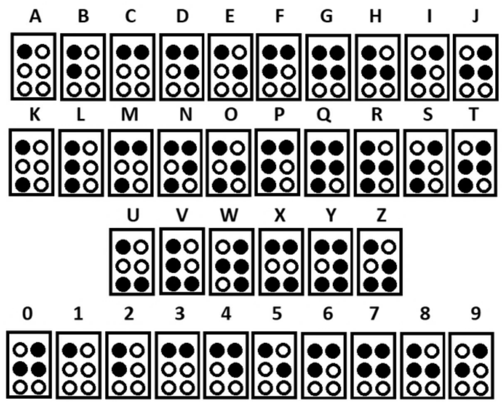

Fig.1. Braille Characters [48]

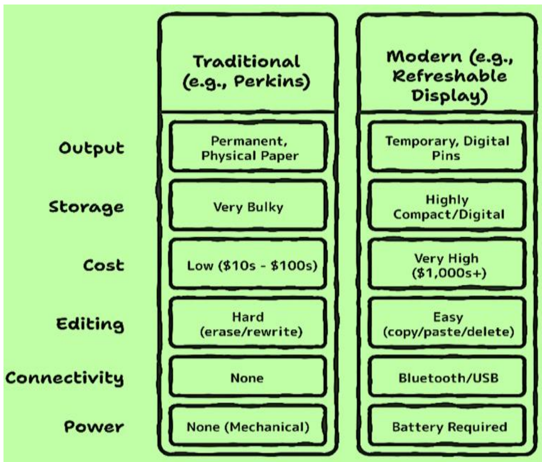

Fig.2. Comparison between Traditional and Modern Braille Devices

Emerging technologies from domains such as mechatronics and IoT have yielded affordable microcontrollers, smart tactile actuators, and AI-driven text-to-Braille converters that enhance portability, affordability, and real-time access. Unlike static embossers, these active displays rely on actuator systems and embedded electronics to dynamically raise and lower Braille dots. Yet, while software frameworks have advanced rapidly, hardware innovation has not kept pace. A visually impaired professional who uses a modern Braille system has noted: “As a Braille user, I can testify that reading Braille enhances cognitive engagement in ways auditory tools cannot. The tactile process of decoding letters and symbols enhances concentration and active learning, offering a deeper interaction with content” [4]. These situations warrant deeper examination, particularly as user expectations grow for affordability, portability, speed, and AI-driven interactivity.

The Fig.2 highlights the evolution of Braille technology from traditional systems to modern electronic devices. While traditional Braille relied heavily on manual methods, such as a stylus and a slate, modern devices integrate digital features, including QWERTY input, file editing, cloud storage, and audio feedback. The shift from tactile-only interaction to multimodal accessibility (tactile + audio) significantly enhances usability for blind users, making modern Braille devices more efficient and better suited for integration with contemporary digital systems. This review examines these advancements in Braille hardware and software technologies, emphasizing their potential to make Braille more inclusive and widely accessible. This review comparatively examines and evaluates the various digital Braille devices currently available in the market, highlighting their key differences and similarities. [5-9].

2. TRADITIONAL AND MODERN BRAILLE DEVICES

2.1 TRADITIONAL BRAILLE DEVICES

Grade 1 Braille is a letter-for-letter substitution of its printed complement. It is the preferred code for the beginners, because it will allow people to get used to it and recognize various aspects of the code while learning.

The literary braille code, Grade 2, uses the “contractions” that substitute shorter sequences for the full spelling of commonly occurring letter groups. The contractions are similar to English print contractions, like “cannot” versus “can’t”, in the way that a word is shortened. For example, “the” is usually a single character in braille (i.e. ⠮) [10].

2.2 PARADIGM SHIFT FROM GRADE 1 TO GRADE 2

The great but fundamental transition in the history of braille users is the paradigm transition from Grade 1 to Grade 2 braille devices which helped the readers to enhance their way of learning, this shift is from basic character recognition to read a comprehension fluently with the shorthand notations. Initially, Grade 1 provides a direct, one-to-one mapping of every character in the print including the alphabet, number, characters; which is essential for building foundational tactile skills without overwhelming the learner. However, the user experience of reading Grade 1 is often slow, it takes more time and effort when reading big comprehensions. The true leap in proficiency occurs with the mastery of Grade 2, which introduces contractions for common words and letter groups. This makes the task of reading simpler and easier for the blind by memorizing symbols for some common words. There might be some difficulty for the fresher while using the product to memorize extra symbols but in the long-term usage they might benefit while reading long paragraphs [46].

2.3 ADVANTAGES AND DISADVANTAGES OF GRADE 2 BRAILLE

When we start comparing the Grade 1 and Grade 2 braille systems it is based on how well it achieves the goal of developing the skill of reading for blind rather than on a general standard of superiority. The primary disadvantage of Grade 2 is the learning to read defined by a steep curve which shows that it is hard at the beginner level. However, Grade 2 users have a drastic increase in the reading speed when compared to the others. It is even bringing closer to the pace of sighted readers or listening to the audio books. It also offers us the solution for spatial problems while converting big physical books into braille; by using contractions; which is useful for both tactile braille displays and physical volumes. So, Grade 2 braille users tend to master their proficiency in reading and it becomes a gateway to comprehensive literacy.

2.4 MODERN BRAILLE DEVICES

Braille Translation Engines (BTEs) are software systems that convert digital text into Braille, enabling accessibility for visually impaired users. BTE, like Liblouis and Duxbury, plays an important role in converting the digital text to readable braille across multiple languages with multiple grades. BRLTTY-like tools enhance the access console for visually impaired users, which ensures a consistent translation for both contracted version (Grade 2 Language) and as well as the uncontracted version (Grade 1 Language), Braille Systems [11]. The Fig.3 represents the difference between Traditional and Modern

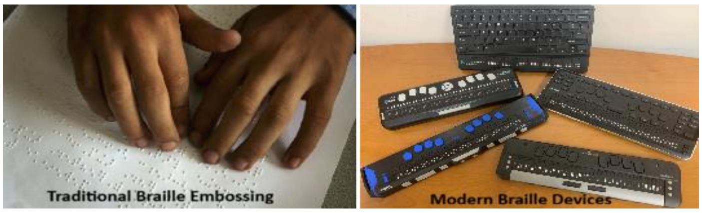

Fig.3. Traditional and Modern Braille devices [49], [50].

The foundational software that supports the Braille displays is only dependent on Operating Systems and Embedded Software and will manage hardware functions in embedded systems for Braille display and translation. These days, Modern Braille devices have come up with lightweight embedded OSes, which support multitasking and device interaction. These operating systems, including Embedded Linux and Android, also enable over-the-air (OTA) software updates, simplifying maintenance and upgrades.

The following standards and methods are used for communication protocols and interfaces to enable data exchange between Braille devices and other systems, which ensure compatibility and connectivity; USB-HID and Bluetooth are being provided with Braille devices for seamless integration with assistive technology. Modern advanced models can do real-time document syncing and remote communications using Wi-Fi with Message Queuing Telemetry Transport (MQTT) or HTTP Application Programming Interfaces (APIs).

Algorithms like the Dot Rendering and Refreshing control the dynamic display and refresh of Braille dots on tactile devices, respectively, ensuring smooth, precise, and accurate content display while still maintaining the appropriate texts. The dot rendering relies on optimized refresh algorithms and frame-buffer techniques, which help in handling large and large data efficiently while still enhancing the readability and visual stability for users.

Integrating the Screen Readers to Braille displays allows a synchronized reading of digital content through both tactile and auditory feedback. Screen readers such as JAWS, NVDA, etc. help the Braille systems maintain high compatibility with the upcoming newer generation of devices. This integration ensures a synchronized and seamless user experience.

With the advent of Artificial Intelligence (AI), there is a paradigm shift in content delivery, enhancing Braille learning and interacting with individual users. Braille content, such as voice-to-text conversion and Large Language Models (LLM) models for summarization, are being enhanced by AI to make it easier for them to understand.

On the other hand, the Natural Language Processing (NLP) simplifies any complex texts into an understandable and simpler text format and also creates a more personalised way of learning, enhancing users' experience, and increasing the learning curve. Cloud-based platforms that provide real-time Braille content conversion, storage, and access, offering scalability and remote access to Braille materials for enhancing the learning capacity. With voice command support and instant feedback, and updates, these solutions promote accessibility and deliver the content over all geographical boundaries.

3. ACTUATION MECHANISMS IN BRAILLE DISPLAYS

This section explores the critical role of actuators the core electromechanical elements responsible for tactile output in Braille displays.

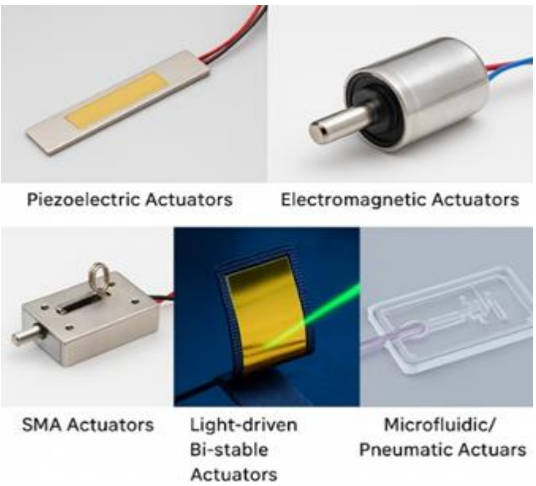

Fig.4. Types of actuators used in Braille devices

It provides an overview of the most commonly adopted actuator types in assistive Braille hardware, including piezoelectric, electromagnetic, shape memory alloy (SMA), pneumatic/microfluidic, and light-driven bi-stable mechanisms, as shown in Fig.4. Each type is evaluated for performance across key parameters such as speed, power consumption, noise, durability, and cost.

3.1 PIEZOELECTRIC ACTUATORS

Piezoelectric (PZT) actuators respond almost instantaneously with zooming pins up and down with a sub-millisecond speed of actuation while drawing minimal power and meagre audible noise. Known for exceptional longevity, many PZT displays operate reliably over a billion cycles of operation [14]. These features make piezo the go-to choice in commercial 40 cell and 80 cell Braille devices. The "Braille Note Touch Plus" utilizes piezoelectric actuators to raise and lower Braille dots with high precision and speed. These PZT actuators expand mechanically in length when voltage is applied, making them ideal for devices that demand silent, fast, and accurate tactile output like the above-mentioned advanced note-taker [15].

3.2 ELECTRO-MAGNETIC (SOLENOID) ACTUATORS

Electromagnetic actuators, often solenoids or cam-shaft based systems, exhibit fast actuation comparable to piezo units, but at moderate energy costs and audible clicks. Their mechanical simplicity supports easier DIY or low-cost Braille implementations, although they tend to be louder and slightly less reliable [16]. They can conserve power efficiently when uncoupled after actuation via electronic latches. The "Easy Braille device" is a compact and cost-efficient display likely using electromagnetic solenoid-based actuators, which move pins via magnetic field induction. These actuators provide a low-cost alternative to piezo actuators but are often bulkier and slightly noisier.

3.3 SHAPE MEMORY ALLOY (SMA) ACTUATORS

SMA actuators, like Nickel Titanium wires or springs, offer compactness and noiseless operation, but endure slower thermal cycles (∼1 Hz) and fatigue over time. Their small form factor suits experimental portable pads [17], though limited durability restricts long-term commercial uses. The "DOT Watch" is a smart Braille wearable, employs SMA-based actuators, leveraging the thermal contraction of shape memory wires to raise dots. This miniaturized actuator solution allows compact design and silent operation, although with limited speed and durability [18].

3.4 MICROFLUIDIC / PNEUMATIC ACTUATORS

Microfluidic-driven Braille cells use pressurized membranes to move pins at medium speed, with silent operation and moderate durability. Microfluidic or pneumatic actuators offer silent and low-power Braille dot control using air pressure, making them suitable for experimental, flexible, or low-cost tactile interfaces. Their compact and lightweight build enables potential portability in future soft robotics and assistive devices [19]. This microfluidic technique allows dense, low-cost arrays, and some of these prototypes have achieved full character accuracy [20]. The design challenges include the complexity in the usage of pumps and valves. A research prototype developed at MIT, USA employs pneumatic microfluidic actuators to control airflow and raise Braille dots through soft robotic structures. These are ideal for low-cost educational solutions but remain largely in lab testing phases [19].

3.5 LIGHT-DRIVEN BI-STABLE ACTUATORS

An emerging class: bi-stable-fibre-reinforced actuators are triggered by light (e.g., laser or LED). Once switched on, they remain stable without power consumption. These offer moderate speed, near-silent operation, and promising flexibility for soft displays, but remain in the research phase with limited real-world deployments [21].

While not used in current commercial devices, light-activated bi-stable actuators have potential in futuristic Braille devices due to their silent, energy-efficient switching and remote triggering features. Ongoing research proposes such systems as upgrades to compact displays like Actilino [22],[31].

3.6 TACTILE ERGONOMICS OF BRAILLE PINS

The size of a Braille pin matters. BANA says dots should be 0.48 mm tall and 1.44 mm wide, with 2.34 mm between dots in a cell [53]. Most manufacturers copy these sizes so people can read both paper Braille and electronic displays without relearning everything.

SMA actuators fail from repeated use. Piezo ones don't fail the same way. That's why most commercial displays use piezo now [54]. So pin design and durability aren't just manufacturing stuff , they directly affect how well you can read and how long the display lasts.

4. CONTROL ELECTRONICS & SIGNAL ARCHITECTURE

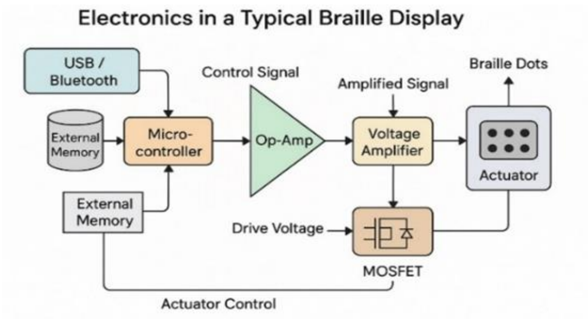

Fig.5. Backend Electronics in a Typical Braille Display

This section delves into the back-end electronics that orchestrate actuator movement in refreshable Braille displays. It outlines the core components such as microcontrollers, MOSFETs, operational & voltage amplifiers, and driver circuits and further explains the typical signal flow from digital Braille input to physical dot activation. Key integration challenges and design considerations are also discussed to guide efficient, low-latency, and power-optimized system development. The Fig.5 illustrates the signal flow in a typical electronic Braille display system. Input data from USB/Bluetooth and external memory is processed by a microcontroller, also conditioned using an op-amp and voltage amplifier, and then driven through a MOSFET to control actuators that raise or lower the Braille dots

Within Control Electronics and Signal Architecture, MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors) act as crucial electronic switches and amplifiers for physically controlling actuators. Microcontrollers, such as those found in Arduino or STM32 platforms, efficiently provide low-voltage signals, but cannot directly drive high-power actuators. This is where MOSFETs become indispensable by handling the necessary higher current and voltage switching. Together, the controller sends a low-voltage signal to the gate of the MOSFET, which then switches power from a higher-voltage supply to the actuator, enabling the actuator to perform its mechanical movement.

Achieving precise and responsive control over an actuator often involves both operational Amplifiers (op-amps) and voltage amplifiers. Op-amps compare sensor input with a reference (setpoint) and output an error signal to adjust actuator behaviour, which are commonly used in feedback control systems. Voltage amplifiers then boost this low-voltage signal from the op-amps or controllers, providing sufficient voltage or current to directly drive the actuators. This is particularly important when actuators require high voltage or power, like piezo actuators. This combined setup allows for accurate and responsive mechanical movement, converting the electrical signal into physical motion, whether proportionally or discretely. Thus, these systems become the backbone for Braille displays in achieving precise actuation.

The MOSFET-driven actuators, responsible for pin movement, are tailored to their operational principles, ensuring smooth and accurate Braille character formation. The synergy of these components allows the system to translate digital signals into tactile outputs, enhancing accessibility for visually impaired users [23,24].

4.1 ELECTRONIC DRIVER FOR PIEZOELECTRIC ACTUATORS

Piezoelectric actuators operate by mechanically deforming under an applied voltage, enabling precise movement of Braille pins. Typically, piezoelectric actuator converts electrical signals into pin movement, op-amps are used for feedback control of displacement, ensuring accurate pin positioning to meet tactile requirements and regulate signals for precise and stable Braille dot positioning, these relations are represented in Fig.6 [23].

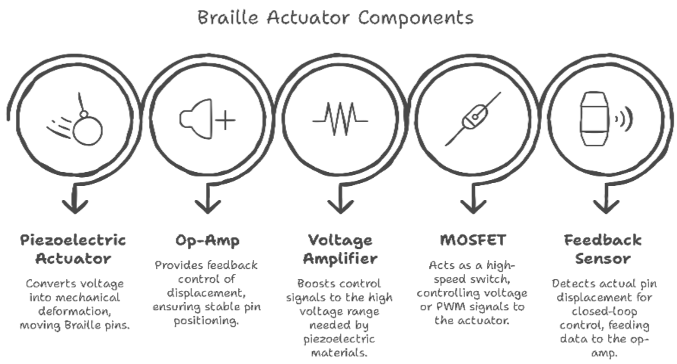

Fig.6. Component Roles for Electromagnetic (Solenoid) Actuators

Voltage amplifiers drive high-voltage piezo actuators, as piezoelectric materials typically require voltages in the range of 10V to 1kV to achieve sufficient displacement. MOSFETs control the voltage or Pulse Width Modulation (PWM) signals, allowing fine-tuned actuation of the piezoelectric elements. This configuration ensures rapid and precise pin movement, critical for real-time Braille display [24].

4.2 ELECTRONIC DRIVER FOR ELECTROMAGNETIC ACTUATORS

Electromagnetic solenoids generate a magnetic field when current flows, moving a plunger to raise or lower Braille pins. Op-amps are employed for current sensing and stabilization, ensuring consistent current flow for reliable operation [25]. Voltage amplifiers amplify the microprocessor's control signals to levels suitable for switching the solenoids, typically requiring 12V for actuation [26]. MOSFETs serve as switches, controlling the solenoid current, enabling precise timing of pin movements. This setup provides robust and reliable Braille character formation, though solenoids may be bulkier than other actuators [25]. These relations are represented in Fig.7.

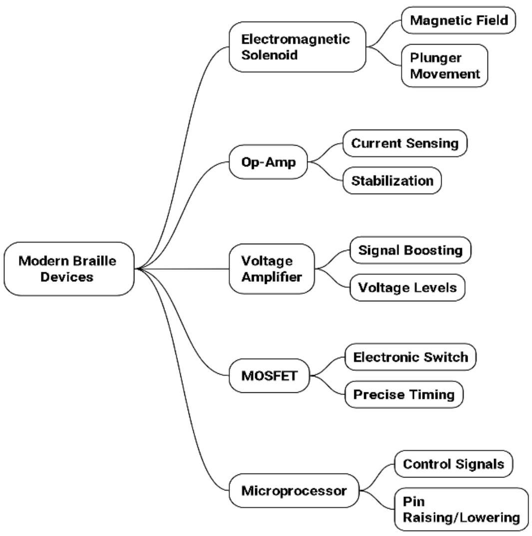

Fig.7. Component Roles for Electromagnetic (Solenoid) Actuators

4.3 ELECTRONIC DRIVER FOR SMA ACTUATORS

SMA Actuators change shape when heated by electrical current and return to their original shape upon cooling. Op-amps monitor temperature via thermistor inputs, providing feedback to prevent overheating and ensure optimal actuation temperature [27]. Voltage amplifiers condition signals and smooth Pulse Width Modulation (PWM) inputs for consistent heating, which are critical for precise shape changes [28]. MOSFETs regulate pulse heating through PWM, controlling the current to achieve the desired temperature and pin movement. This relations of components in the SMA actuator device are represented by Fig.8. SMA actuators offer an advantage in terms of compact design [26].

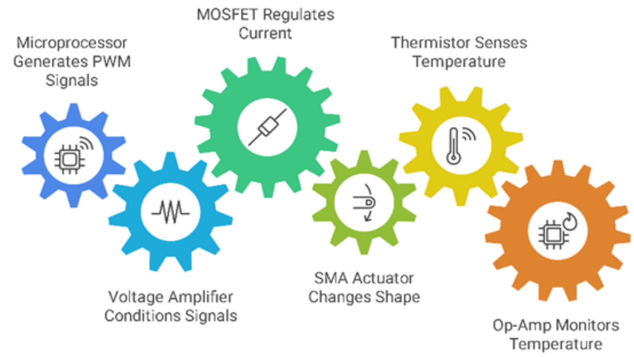

Fig.8. Electronic Components and Their Roles for SMA-Actuators.

4.4 ELECTRONIC DRIVER FOR LIGHT-DRIVEN BI-STABLE ACTUATORS

Light-driven Bi-stable Actuators, though not widely documented in commercial Braille displays, may involve photo-sensitive materials that change shape under light exposure. As shown in Fig.9, Op-amps likely regulate the current to LEDs or lasers, ensuring stable light intensity. Voltage amplifiers drive the light source to achieve the necessary intensity for actuation. MOSFETs switch or modulate the light source, controlling the timing and intensity of light exposure to actuate the pins. Due to limited evidence, this actuator type may represent an experimental approach, potentially offering energy efficiency for future Braille displays.

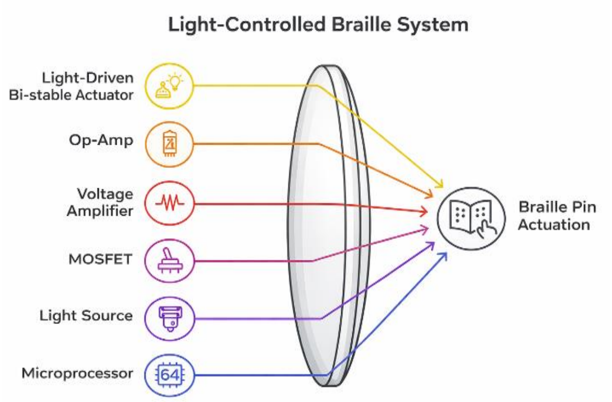

Fig.9. Various Electronic Components and Their Roles for Light-Driven Bistable Actuators

4.5 ELECTRONIC DRIVER FOR MICROFLUIDIC/ PNEUMATIC ACTUATORS

Microfluidic/pneumatic actuators use fluid pressure/air pressure, respectively to move Braille pins, offering a compact and low-power alternative. The principle-Op-amps provide feedback control for pressure or valve positions, ensuring accurate pin movement [29]. Voltage amplifiers amplify signals to drive solenoid valves that control air flow, which typically requires precise signal levels [30]. MOSFETs switch these solenoid valves, regulating air pressure to raise or lower pins. This system is particularly effective for applications requiring multiple actuators, as demonstrated in soft robotics and Braille displays [29].

Fig.10. Component Roles for Microfluidic/Pneumatic Actuators

Piezoelectric actuators offer precision, solenoids provide robustness, SMA actuators enable compact designs, light-driven bi-stable actuators suggest future potential, and microfluidic/pneumatic actuators offer low-power solutions. The evidence leans toward piezoelectric and solenoid actuators being the most common, with SMA and pneumatic systems gaining traction, while light-driven bi-stable actuators remain experimental. This integration ensures reliable and accessible tactile feedback for visually impaired users. The Table.1 represents components role in Sync with Actuators.

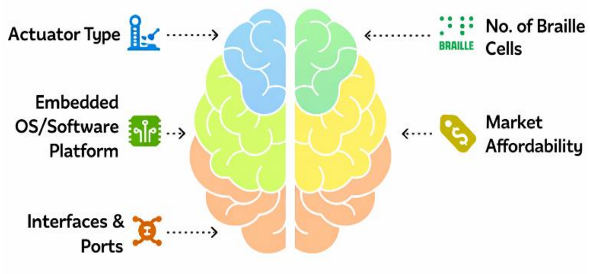

Fig.11. Key Factors in Device Functionality

4.6 POWER SUPPLY DESIGN FOR MULTI-CELL ARRAY

Beyond individual actuators, the power supply subsystem is what determines whether a Braille display can sustain reliable operation across many simultaneously working cells. It is found that most portable refreshable braille devices draw either from lithium-ion or lithium- ion battery, which is regulated through Battery Management System (BMS). BMS monitors voltage, current and temperature while protecting against thermal events, over-discharge and overcharge; and this is a standard engineering practice in low-cost embedded builds, as documented in dedicated BMS design literature [51].

A regulator stage then steps the battery's nominal voltage up to the actuator rail, since normal piezoelectric elements requires 10V to 1kV while solenoid requires around 12V (Section 4.1 – 4.2); the regulator's transient response becomes very critical when many pins actuate within the same refresh scale, as an under-damped supply will sag under this current spike and produce incomplete pin displacement.

For multi-cell arrays the power sequencing, staggering actuation across all cell groups rather firing all pins simultaneously, reduces the peak inrush current and gets a smooth demand on battery. And this is not merely a theoretical but a working refreshable Braille prototype built around Raspberry Pi controller driving around 126 micromachined Braille cells through cascade shift registers which used exactly the combination of a Li-iron cell and a dedicated BMS to power full array reliable [52].

4.7 FAULT TOLERANCE

A Braille display needs to detect stuck pins. One stuck pin ruins a character, which is worse than blank. Manufacturers patented dust-resistant housings because pins "often become stuck when fouled by contaminates" [58].

The fix is simple: tell a pin to move, check if it moved, flag the mismatch as a fault, and report it to the system [59]. This catches real failures (pin never moves) versus temporary glitches that fix themselves. Most commercial displays don't document which methods they actually use.

Table.1. Components Role in Sync with Actuators

Actuator Type	Op-Amp Role	Voltage Amplifier Role	MOSFET Role
Piezoelectric (PZT) [24]	Feedback control of displacement for precise pin positioning	Drives high-voltage piezo elements (10 V-1 kV)	Controls voltage or PWM for actuation
Electromagnetic (Solenoid) [25], [26]	Current sensing and stabilization	Amplifies the control signal (e.g., up to 12 V)	Switches current to the solenoid
Shape Memory Alloy (SMA) [27], [28]	Temperature feedback via thermistor input	Conditions, signals, and smooths PWM for heating	Regulates pulse heating using PWM
Light-Driven Bi-Stable [31]	Regulates LED/laser current intensity	Drives the light source for activation	Switches or modulates the light source for actuation
Microfluidic/Pneumatic [29], [30]	Feedback control for pressure or valve positions	Drives solenoid valves for air or fluid control	Switches solenoid valves to modulate pin actuation

Table.2. Quantitative Performance Comparison of Actuator Types

Actuator Type	Actuation Force(g)	Refresh Rate (Hz)	Power (mW)	Cycle Life	Response Time
Piezoelectric (PZT) [23,24,60]	15–30	50–200	1–5	$>10^9$	Practical Braille cell settling ≈ 25–150 ms
Electromagnetic (Solenoid) [16,25,61]	20–50	10–50	30–80	10^6–10^7	≈130 ms actuation, ≈56 ms return

Shape Memory Alloy (SMA) [27,28,62]	5–20	0.5–2	50–200	~10^5	≈1 second (300 mA drive current)
Microfluidic / Pneumatic [19,20,29,62]	2–10	5–20	10–40	Not reported	≈60 ms demonstrated in one Braille design
Light-Driven Bi-Stable [21,31,63]	Not reported	~1–5 (est.)	≈0 (bistable)	Not reported	*No standardized Braille-specific response time found.

Note: Values represent reported ranges from cited literature. Force output is the tactile pin force at rated displacement. Power per cell is the steady-state draw during active refresh. Cycle life figures are manufacturer or laboratory-reported under standard test conditions. "Not reported" indicates no quantitative data was available in the sources reviewed. Superscript exponents denote powers of ten.

*Highly dependent on mechanism. Modern bistable systems typically switch in milliseconds, while photothermal systems may require tens to hundreds of milliseconds.

Response time is another important parameter when comparing actuator technologies because it directly influences the refresh performance of a Braille display. As shown in Table 2, piezoelectric actuators exhibit the fastest response, whereas SMA actuators are considerably slower due to the heating and cooling process involved. Electromagnetic and pneumatic actuators fall between these two extremes, offering moderate response times while maintaining different trade-offs in power consumption and complexity. When considered together with force, refresh rate, power consumption, and cycle life, these metrics provide a clearer engineering comparison of the available actuator technologies.

5. DEVICE SOFTWARE ARCHITECTURES

Each leading refreshable Braille device adopts a distinct software stack that balances performance, portability, and accessibility.

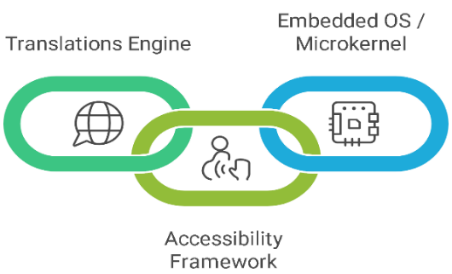

Fig.12. Software Architectures in Braille

Orbit Reader 20 has 20 braille cells with Bluetooth/USB connectivity, and a Perkins-style keyboard is used. It is affordable and portable, but limited by its small size. It uses an electro-mechanical cell. It is priced at USD $799.00, which is a budget-friendly choice. The Orbit Reader 20 runs on an embedded Real-time Operating System. It was the first braille display to support the USB HID standard. Its architecture emphasises affordability and durability, foregoing features commonly available now on smartphones and computers, in favour of stability and rugged use in developing regions [32]. The Fig.12 represents the key software architectures that are present in modern braille devices.

BrailleNote Touch Plus offers an 18-cell and 32-cell display with cursor-routing keys, inbuilt Wi-Fi, Bluetooth, and USB connectivity, and Android compatibility. Piezoelectric actuators are used for efficient refresh performance. Priced at $6,000, it is a premium device with functionality comparable to a general-purpose tablet. The Braille Note Touch Plus combines silent, force-free typing via Touch Braille with an intuitive Android interface and integrated visual display, enabling seamless collaboration with sighted users. Its powerful Key Soft suite supports document creation, web browsing, and math input, while access to Google Play expands its versatility. Users benefit from tactile navigation on an 18 or 32-cell Braille display, customizable TTS engines, and gesture-based controls. With Bluetooth, HDMI, USB, and SD support, plus a user-replaceable battery, it delivers robust connectivity and personalised accessibility in a compact, feature-rich package [33].

Braille Star 80 includes an 80-cell display with built-in speech, Bluetooth and USB connectivity, and cursor routing. Its audio feedback is a noted strength, though the device is bulky and high in cost. Advanced piezoelectric actuators support its performance. Priced at $9,995, it is designed for professional and high-demand users. The Braille Star 80 is a robust workplace-oriented Braille system featuring 80 concave piezoelectric Braille cells with integrated cursor routing and triple-action keys. Optimized for dual-PC control, it supports both USB and serial interfaces with seamless manual switching. The system includes a user-configurable 16-key pad, ergonomic Braille entry keys, and internal notetaking with up to 512 editable files and 3MB per file. The HTCom software, which enables the real-time data synchronization with Personal Computers (PC's) and the Grade 2 Braille translation. It is compatible with screen readers, with 2 audio stereo ports making it a fully furnished Braille terminal [34].

The Seika series, which is made by Nippon Telesoft Co. Ltd, comprises the v3, v3Pro, v5, and v80 devices, offering versatile and portable Braille devices, which are designed for seamless and continuous connectivity and portability, which has become a key feature and benefit of this device. Most of the models have 8-dot refreshable Braille displays, with the v3Pro and v5 offering 40-cell displays and the v80, which extends to 80 cells for longer content visibility. These devices are equipped with 8 cursor keys, each having its own purpose of usage. The 8 function keys can synchronise with computers and other devices, which increases efficiency at work. While the Seika v5 model uniquely provides a USB-A lead port and Bluetooth support for mobile devices or tablets and it is also powered by a lithium rechargeable battery, which will provide extended 8 hours of runtime. The V5 model has a form factor weighing around 600g and is designed with a display size of 13×4×1 inch. The Seika devices generally are covered with leather covering, making them ideal for visually challenged students in the educational wing and professionals [35].

Actilino 3.0 is a portable 16-cell Braille display with audio feedback, Bluetooth/USB connectivity, and built-in learning tools like note-taking. It is affordable and compact, but limited by its small display size. It uses piezoelectric bimorph actuators [36,37]. Actilino 3.0 is priced at $2,750, making it accessible for entry-level users. The Actilino 3.0 braille device is an ultra-compact and portable device, having a dual-purpose. One is a Braille display, and the other is the Note Taker feature, which is designed for mobility and efficiency. This will enable users to create and access notes without dependency, and also enhance the learning curve and productivity. It has 16 concave piezoelectric braille elements having cursor routing and has a unique feature named Active Tactile Control (ATC), which supports uninterrupted and seamless reading without scrolling manually. The device has dual space bars, including polyphonic audio in it, and also has an integrated microphone and speakers which will assist the users in communication via different applications. The device can interface with up to four devices simultaneously. It also offers 16GB onboard storage, a 30-hour battery life, and compact ergonomics (6.5″ × 4.3″ × 1.1″, 0.92 lb), making it a powerful companion for both professional and personal use. Refer the Fig.13 for pictures of the devices mentioned above.

6. SOFTWARE COMPONENTS IN BRAILLE DEVICES

In this context of assistive technology, software plays a far more dynamic role than hardware. While hardware upgrades often require significant cost and time, software can evolve rapidly, enabling frequent enhancements and advancements in accessibility, usability, and compatibility. Through over-the-air (OTA) updates, integration of AI-based personalization, and support for modern Application Programming Interfaces (API), software has become the vehicle through which Braille devices continue to adapt to emerging user needs without altering their physical form.

Fig.13. Modern Braille devices mentioned in the current review paper namely - a. OrbitReader20; b. BrailleStar80 c. Seika80; d. BrailleNoteTouch+; e. Actilino 3.0 [32]-[37].

While hardware forms the tactile backbone of Braille devices, it is the embedded software stack that drives functionality, accessibility, and personalization. Software governs the refresh logic, translation precision, and interface with screen readers. Notably, software evolves faster than hardware, enabling updates, feature expansion, and multilingual support post-deployment, thereby making devices more inclusive and sustainable. In essence, hardware without software is dormant, and software without hardware is intangible. Their synergy empowers the visually impaired in dynamic, meaningful ways.

6.1 SOFTWARE METRICS AND TRADE OFFS

The software stacks of the reviewed Braille devices vary in complexity and capabilities.

Orbit Reader 20: The RTOS is simple and highly efficient. However, the firmware is quite complex, running across multiple processors to control the braille cells and deliver application and user interface functionalities. The Orbit Reader 20 supports all major screen readers available in the market and is widely recognized as a reference braille display by most screen reader vendors. The Orbit Reader 20 has a powerful translation engine developed in-house with Indian and foreign language braille experts. The Tactuator™ technology developed by Orbit Research provides the highest quality of braille in the world and is commonly referred to as “signage quality” braille. Unlike other technologies, the technology does not consume any power once a refresh is complete [32]. In contrast, the Braille Note Touch Plus operates on full Android with the Key Soft suite, providing advanced accessibility via Talkback, JAWS, and Liblouis-powered Grade 2 translation, reflecting high OS and firmware complexity [33].

Braille Star 80 employs dedicated firmware with HTCom for Grade 2 translation and dual-PC switching, offering moderate complexity with strong local file handling [34]. The Seika series emphasizes portability and compatibility with screen readers like NVDA and JAWS, maintaining low firmware complexity while supporting USB and Bluetooth (v5 only) [35]. Actilino 3.0, with its ATC (Active Tactile Control) technology, supports seamless reading across devices via Bluetooth/USB and offers simple yet efficient multitasking. Regarding dot rendering, Braille Note’s Touch Braille and Actelion’s ATC provide optimized tactile feedback, while Braille Star’s triple-action keys and cursor routing enhance navigation. Orbit focuses on durability over rendering sophistication. Devices differ significantly in OS architecture, translation integration, and real-time dot rendering based on their design goals [37].

The software design of Braille devices varies significantly, reflecting different engineering priorities. A clear spectrum exists, ranging from the high complexity of full-fledged operating systems like Android in the Braille Note Touch Plus to the simple, efficient RTOS of the Orbit Reader 20. Key differentiators lie in the operating system architecture, the integration of translation engines (whether in-house or third-party), and the sophistication of dot rendering technologies like ATC and Tactuator™.

The Table.3 represents a comparative analysis and overview of the leading refreshable Braille devices based on market characteristics and also software-specific metrics. It includes information on braille devices, such as the country of origin, launch period of the device, the popularity gained by the device, pricing range, and notable and important software features that distinguish each product and make an impact. This allows us to do a comprehensive assessment of their design intent, usability focus, and accessibility reach.

Table.3. Comparative Overview of the leading Refreshable Braille Devices

Device Name	Country of Origin & Manufacturer	Release Year	Price Range (₹)	Popularity	Key Features (Software)
Orbit Reader 20 [32]	USA (Orbit Research)	2016	₹45,000 – ₹55,000	High (global reach)	20-cell, 8-dot Braille cells, Embedded Linux + BRLTTY; Refresh rate ~100 Ms; USB/Bluetooth; Screen reader support: JAWS, NVDA, Voiceover; 3–5 hrs battery backup; Multilingual support
Braille Note Touch+ [33]	Canada (Human Ware)	2019	₹2.8L – ₹3.2L	Very High (academic)	18/32 cells; Android 11 OS; Liblouis (Grade 2); Google Play apps; Touch Braille typing; HDMI, USB, Wi-Fi, Bluetooth; NVDA, Talk Back; ~10–12 hrs battery backup
Braille Star 80 [34]	Germany (Handy Tech)	2014	₹4.5L – ₹5.5L	Medium (office use)	80 concave piezo Braille cells; Dual-PC mode; USB/Serial connectivity; HTCom for PC sync; Screen reader support: NVDA, JAWS; ~5 hrs battery; Multilingual Braille translation
Seika v3Pro/v5/v80 [35,41]	Japan (Nippon Telesoft)	v3Pro: 2020, v80: 2022	₹90,000 – ₹1.4L	Moderate (portable use)	40/80 8-dot Braille cells; USB (v3Pro), USB/Bluetooth (v5); NVDA, Supernova, JAWS; Refresh speed moderate (~150 Ms); v5: 8 hrs battery; lightweight; multilingual support
Actilino 3.0 [36]	Germany (Handy Tech)	2023	₹2.3L – ₹2.8L	Moderate (mobile users)	16 piezo Braille cells with ATC; USB-C, Bluetooth; Polyphonic audio, microphone; Cursor routing keys; 30-hr battery life; Real-time auto-scroll; Screen reader compatible
Dot Pad [18]	South Korea (Dot Inc)	2022	₹8.75L-10.51L	Very High (innovation)	2400 electromagnetic pins and 20 braille line text; USB-C, Bluetooth; compatible with iOS and iPadOS; Portable and high battery life [38]

6.2 IDEAL CONDITIONS FOR A BRAILLE DISPLAY

To evaluate the suitability of modern refreshable Braille devices for diverse user needs, we propose a set of ideal design criteria, labelled A through G. These metrics reflect a comprehensive vision for inclusive and future-ready Braille technology. The analysis of our ideal conditions to some prominent devices has been shown in Table.4.

6.2.1 List of Criterion:

1. Display Size: Refers to our ideal display size of 27×9 cells, suitable for a standard page formatting.
2. Graphical Support: Assesses the support for graphical and mathematical Braille content.
3. AI–Driven Multimodal Input/Output Facility: Evaluates the presence of AI-driven multimodal input/output for users with additional impairments.
4. Affordability: It considers affordability, especially for users in developing countries (≤ ₹40,000 / ~$500).
5. Multi-Age Usability: Multi-age usability across educational and professional settings.
6. Enhancing and Interactive Features: It captures cognitive and interactive features aimed at enhancing learning experiences, particularly for children.

These six criteria align with real standards. ISO/IEC 24751 covers criteria C and E in your table [56]. WCAG 2.1 (the web accessibility standard) covers criteria B and F [57].

These standards also influence the way modern refreshable Braille displays are designed. ISO/IEC 24751 emphasizes adaptability and personalized accessibility, encouraging assistive technologies to accommodate users with different learning styles, abilities, and educational requirements. In the context of refreshable Braille displays, this supports features such as AI-assisted interaction, multimodal feedback, and interfaces that remain usable across different age groups and learning environments. Similarly, although WCAG 2.1 was originally developed for digital and web accessibility, many of its principles extend naturally to refreshable Braille technology. Compatibility with screen readers, support for mathematical and graphical content, accessible navigation, and standardized accessibility APIs all contribute to making Braille displays more effective as digital access devices rather than simple text readers

But there’s a gap. Refresh rates vary wildly (0.5–2 Hz for SMA, 50–200 Hz for piezo) and there’s no standard minimum. BANA set physical dot sizes in Section 3.6, but nobody standardised how fast cells need to update. This makes it hard for schools to know what’s acceptable when buying a device.

As refreshable Braille technology continues to evolve, establishing common performance standards would benefit both manufacturers and users. While current standards define the physical characteristics of Braille, they do not specify engineering performance metrics such as refresh rate, response time, tactile force, durability, or power consumption. Defining such benchmarks would allow future devices to be evaluated more consistently, simplify procurement for educational institutions, and encourage the development of Braille displays that are not only accessible but also comparable in terms of performance and reliability.

Table.4. Analysis of Ideal Conditions Across Leading Braille Devices

Device Name	A	B	C	D	E	F	Remarks
Orbit Reader 20 [32]	✗	✗	✗	✓	✓	✗	Cost-effective & robust; lacks graphics, AI, and advanced interactivity
BrailleNote Touch+ [33]	✓	✓	✓	✗	✓	✓	Near-complete functionality; expensive but feature-rich with AI & Touch
Braille Star 80 [34]	✓	✗	✗	✗	✗	✗	Stationary with 80 cells; lacks mobility, AI, and modern educational features
Seika Series (v3/v5/v80) [35]	✗	✗	✗	✓	✓	✗	Good portability & screen reader support; no AI, graphics, or rich interactivity
Actilino 3.0 [36]	✗	✓	✓	✗	✓	✓	Smart and AI-integrated; compact size limits cell range, high cost

7. USER-CENTRIC REVIEWS AND INSIGHTS ON AI IN BRAILLE DEVICES

Specifying the technical aspect of the refreshable braille displays is crucial for real-life applications. User reviews and community feedback provide a broad perspective, highlighting a persistent trade-off among affordability, advanced functionality, and reliability. Orbit Reader 20 is frequently praised for its low price point, making it a viable option for students and users in developing regions. However, this affordability comes at the cost of not having certain features. As one review highlights, the device is "intended primarily as a braille display" and lacks "onboard translation options, Cursor Routing Buttons" [38]. The review states that it is a durable and functional tool at its price point, solely focusing on cost-effectiveness.

Conversely, devices at the premium end of the market, such as the BrailleNote Touch+, face scrutiny over their value proposition and software longevity. While offering a capable Android-based solution, user feedback points to drawbacks that weigh against the high cost. One review notes reliance on an "outdated Android 8.1 system" and the mandatory Google account requirement as significant barriers, particularly for users less familiar with modern platform ecosystems [39]. This sentiment is echoed across forums, where users question the expense when a more affordable Braille display paired with an up-to-date smartphone can offer superior performance and access to the latest AI-driven applications. This perspective highlights a critical issue: a device's "smart" capabilities are only as good as its software, and obsolescence can quickly erode its value. The professional user's perspective offers another dimension, particularly for large-format displays like the Braille Star 80. For users working with complex documents, spreadsheets, or programming code, the 80-cell display is not a luxury but a necessity for productivity. Feedback emphasizes the value of "showing more content at once" and the ergonomic benefits of cursor routing keys for efficient navigation in a workplace setting [40]. For this user segment, the high cost and lack of portability are often acceptable compromises for a specialized tool that enhances their professional workflow. However, these devices remain inaccessible for general use, confining them to a niche market and highlighting the need for more versatile, cost-effective multi-line solutions.

For the growing number of mobile and interconnected users, portability and seamless connectivity are paramount, yet reviews for devices like the Seika series and Actilino 3.0 reveal persistent issues. Users frequently report Bluetooth connectivity failures, where devices cannot be paired reliably with smartphones and require repeated troubleshooting. One user describes having to constantly "go into Voiceover settings, re-select device" to re-establish a connection with their iPhone [41]. While the core Braille output is often described as "good, solid Braille" and the devices are commended for being great for "quick notes and interacting with I-devices," the unreliable connectivity undermines their primary use case as portable companions [42]. This feedback reinforces that even with responsive keyboards and quality Braille cells, an unstable connection creates a significant barrier to a smooth user experience.

In conclusion, these user-centric insights demonstrate that the ideal Braille device is not defined by a single metric but by a balanced execution of functionality, reliability, and value. While technical innovation in actuators and AI integration is required and should be researched, user feedback consistently prioritises practical importance: a stable connection, a clear software update path, and a price point that aligns with the offered functions. The gap between a device's on-paper specs and its real-world usability suggests that future designs must place greater emphasis on software stability, long-term support, and user experience to create technologies that are not just powerful but also dependable and truly empowering.

8. DISCUSSION

The data in Table.4 collectively reveal a structural tension that runs across the entire device landscape: the features users need most are distributed across devices that do not share a common price band. BrailleNote Touch Plus satisfies five of the six ideal criteria in Table 4 and is the only device in this review with verified AI-driven input, graphical Braille support, and multi-age usability, yet it is priced beyond the reach of most users in developing regions. The Orbit Reader 20, by contrast, meets the affordability criterion and demonstrates strong durability, but fails on every feature-related criterion. No single device currently satisfies all six ideal conditions simultaneously.

The quantitative actuator data in Table 2 reinforces this picture from the hardware side. Piezoelectric actuators dominate commercial designs for good reason: they offer the highest cycle life (>10^9 cycles) and the lowest per-cell power draw (1–5 mW), which directly supports the long battery lives reported in Table 3 (e.g., 30 hours for the Actilino 3.0). Electromagnetic solenoids remain the go-to choice for lower-cost implementations, trading higher power consumption (30–80 mW per cell) for simpler driver electronics and lower component cost. SMA actuators present a genuine miniaturization advantage, as seen in the Dot Watch, but their thermal refresh limit of approximately 1–2 Hz makes them impractical for fluent reading, where experienced users require 20–40 cells per second of new content. The gap between SMA refresh rates and fluent reading demand is roughly one order of magnitude, and closing it would require either novel alloy compositions or hybrid actuation schemes.

The software analysis across Sections 5 and 6 reveals an equally important trade-off between OS complexity and long-term supportability. Devices running full Android, such as the BrailleNote Touch Plus, gain access to a wide application ecosystem but inherit Android's update deprecation cycle. A device launched with Android 8.1 in 2019 was already on a legacy OS within three years of release. By contrast, the Orbit Reader 20's custom RTOS, while limited in feature scope, carries no such deprecation risk. For designers, this suggests that a hybrid architecture, a minimal RTOS for core Braille rendering with a sandboxed, updatable application layer for AI and connectivity features, may represent a more sustainable long-term approach than adopting a full consumer OS.

Taken together, these findings point to three design priorities for the next generation of Braille hardware. First, piezoelectric actuation should remain the default for devices targeting extended daily use, given its superior cycle life and power profile. Second, software stacks should be architecturally separated into a stable core and an upgradeable application shell, to avoid the OS obsolescence problem observed in current premium devices. Third, accessibility pricing remains the most critical unsolved problem: the reviewed devices span a cost range of over 20:1 (₹45,000 to ₹10.51 lakh), and the devices with the widest feature sets sit firmly at the expensive end. Addressing this gap likely requires component cost reduction through volume manufacturing or open-hardware initiatives, rather than software optimization alone.

9. IMPLICATIONS AND FUTURE DIRECTIONS

Our findings reveal that software design choice of OS, firmware modularity, API breadth, and translation/rendering algorithms drive critical performance differences. Devices that invest in on device AI plugins and real time drivers demonstrate how advanced software can offset hardware constraints to deliver seamless user experiences. One could advocate for open firmware architectures with pluggable translation modules (e.g., Liblouis + custom NLP), robust OTA mechanisms, and standardized accessibility APIs to foster interoperable ecosystems. These advances will enable next generation Braille displays that are both highly responsive and easily extensible, strengthening inclusive education tools for visually impaired learners.

Going from 80 cells to a full page (243 cells) is not simple. One prototype used decoder chips and shift registers on each cell so the control could update individual cells without breaking the shared bus [55]. This is the key, you reduce the address lines needed.

Refresh timing gets harder at scale. The prototype only refreshed cells that changed, which is what your DDC algorithm does. At full page size this matters because refreshing all 243 cells in order creates visible waves when your finger moves [55]. Also power draw goes up a lot.

Beyond the hardware challenges, scaling to full-page Braille displays also places greater demands on the control electronics and embedded software. Larger actuator arrays require more sophisticated addressing schemes, improved synchronization between controller modules, and efficient power management to ensure stable operation during continuous refresh cycles. Software also plays an increasingly important role by coordinating selective updates, reducing unnecessary actuator movement, and minimizing latency during reading. These considerations highlight that future full-page Braille displays will depend not only on advances in actuator technology but also on improvements in system architecture, firmware design, and energy-efficient control strategies.

One future direction explored through this review is the Differential Dot Configuration (DDC) algorithm, which minimizes unnecessary pin actuations during Braille page transitions. Rather than redrawing an entire page, DDC computes the bitwise difference between the current dot state and the target state, then actuates only the pins that must change. The algorithm operates as follows:

```
DDC(current_state[N], next_state[N]):
  diff_mask = XOR(current_state, next_state)
  FOR i = 0 TO N-1:
    IF diff_mask[i] == 1:
      actuate_pin(i, next_state[i])   // raise or lower
```

where, N is the total number of dots per page (e.g., $N = 480$ for an 80-cell display with 6 dots per cell). The algorithm has time complexity $O(N)$ and requires $O(N)$ additional space for the difference mask, making it suitable for real-time embedded execution. As a worked example, consider a transition between two consecutive sentences on a 20-cell display ($N = 120$ dots). If 38 of the 120 dots must change state, a full-page reset actuates all 120 pins, whereas DDC actuates only 38—a reduction of approximately 68%. Assuming a piezoelectric cell draws 3 mW per actuation event and a refresh rate of 10 Hz, this translates to a power saving of roughly 2.46 mW per cell per second in that transition, which compounds significantly across thousands of page turns in continuous reading sessions. Formal validation of these estimates through hardware simulation or instrumented prototype testing is identified as a priority for future work.

10. CONCLUSION

This review establishes that the advancement of refreshable Braille displays is fundamentally driven by the interactive co-design of hardware and software. Our analysis of actuation mechanisms, ranging from the dominant piezoelectric systems to emerging alternatives, along with their requisite control electronics, highlights how the physical layer influences performance, cost, and tactile fidelity. This hardware foundation is brought to life by a sophisticated software layer, where operating systems, accessibility APIs, and AI-driven features transform these devices into dynamic, inclusive tools. The current market, featuring a spectrum from the affordable Orbit Reader 20 to the versatile BrailleNote Touch Plus, directly reflects the diverse outcomes of these hardware and software integration strategies.

Key challenges persist across the field: inconsistent over-the-air (OTA) updates leave devices running outdated software, fragmented platform support limits interoperability, and the high cost of advanced hardware narrows accessibility. One proposed response to these constraints is the Differential Dot Configuration (DDC) algorithm. By reducing the number of pin actuations per refresh cycle, DDC lowers energy consumption and extends display lifespan, offering a software-level path toward more sustainable Braille hardware.

Looking forward, the development of next-generation Braille displays requires a holistic and unified approach. The future lies in creating open, modular architectures that integrate robust accessibility APIs and pluggable AI capabilities, allowing the technology to evolve seamlessly. By combining hardware innovations with intelligent software solutions like DDC, the field can move towards creating devices that are not only more powerful and interactive but also fundamentally more affordable, adaptive, and inclusive. This forward-thinking strategy will ensure that visually impaired individuals are empowered with effective tools for literacy and equal access to the digital world.

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