Dots: A Frugal Refreshable Tactile Dot Grid for Students with Visual Impairments

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Abstract. Disciplines such as mathematics, computer science, and economics rely heavily on visual representations, creating significant barriers for visually impaired (VI) students in classroom environments. Current assistive technologies are either prohibitively expensive, difficult to implement, or fail to provide immediate tactile feedback during live instruction. This paper introduces a novel tactile display system designed to bridge this accessibility divide through real-time conversion of visual content into tactile feedback.

Our solution consists of an instructor-focused image capture and processing system and a student-focused 55 × 75 tactile pin matrix in an A4 format. The approach employs low-cost hardware components, open-source computer vision algorithms, and a modular design to create an affordable alternative to commercial solutions. Cost analysis confirms this system can be produced at approximately 25% of comparable commercial alternatives, potentially reducing participation barriers for VI students in STEM fields.

Keywords: Assistive Technology · Visual Impairment · Tactile Display · Inclusive STEM Education · Real-Time Tactile Feedback

1 Introduction

Visual representations form the foundation of STEM education by employing graphs, diagrams, and spatial models frequently in its teaching pedagogy. This creates significant barriers for students with visual impairments (henceforth referred to as VI students), particularly in resource-constrained Indian educational environments. With India housing approximately 4.95 million blind and 35 million visually impaired individuals — representing about a quarter of the global VI population [11] — this challenge demands urgent attention. Despite India's 2016 Rights of Persons with Disabilities Act mandating inclusive education [12], VI students remain systematically excluded from this academic sphere due to resource limitations, inadequate teacher training, and awareness gaps [6].

Current assistive technologies are prohibitively expensive in the Indian context: commercial refreshable Braille displays cost $5,500–$8,000, while tactile

C. Stephanidis et al. (Eds.): HCII 2025, CCIS 2524, pp. 194–205, 2025.
https://doi.org/10.1007/978-3-031-94156-6_21

graphics systems range from \$12,000–\$22,500 [9,10,15]. A survey of 185 university libraries revealed only 22.07% had any assistive technology access, with merely one institution (0.54%) providing tactile pathways for STEM instruction [1]. This affordability gap particularly affects the estimated 90% of all visually impaired people, those in low-income settings [16], effectively excluding them from meaningful STEM participation.

Beyond economic barriers, existing solutions predominantly address biological accessibility while neglecting the crucial psychological and social dimensions of learning [6]. Most systems lack real-time content conversion capabilities, preventing synchronous classroom participation and reinforcing educational disparities.

This paper presents a low-cost, real-time tactile display system specifically designed for Indian STEM educational contexts. With an estimated production cost of approximately \$3,000–\$3,500, the system achieves at minimum a 75% cost reduction compared to existing solutions while offering larger resolution. Beyond its immediate educational application, this work has the potential to increase VI student participation in STEM fields, reduce educational disparities, and subsequently contribute to greater economic independence for individuals with visual impairments in India [11].

2 Literature Review

The development of tactile graphics technologies represents a critical area of innovation in assistive technology research. This section examines current landscape of tactile display technologies for visually impaired users, analyzing their approaches, capabilities, limitations, and relevance to educational contexts in resource-constrained environments.

The majority of contemporary refreshable tactile displays utilize arrays of mechanically actuated pins, evolving significantly since the pioneering Optacon (Optical-to-Tactile Converter) of the 1970s [4]. Modern high-end solutions have dramatically expanded these capabilities, though they remain financially inaccessible to most educational institutions. The DotPad employs 2,400 electromagnetic actuators in a tablet format [7], yet costs approximately \$12,000 USD [15]. Similarly, the Graphiti features 2,400 controllable pins in a 60×40 grid with multi-height capability [13], but its $\approx$ \$22,500 USD price point creates significant adoption barriers [14]. The HyperBraille offers 7,200 pins for detailed graphics while enabling bimanual interaction [8], though like its counterparts, this design lacks emphasis on affordability.

Recognizing cost barriers, researchers have explored alternative mechanical approaches. The Tactilia system leverages Nitinol — a shape memory alloy that deforms when heated [3]. The Braille PolyPad features a 4×10 Braille cell display employing pneumatic actuation with a stiffness-variable polymer, achieving rapid switching times (0.5 s regardless of cell count) and reduced component costs [17]. Another approach attaches a small grid of pins to a movable device, creating a “window” into a larger virtual tactile space — reducing required actuators however increasing users' cognitive load [9]. Commercial attempts include the BliTab which promised tablet functionality using a smart liquid to create bubble-like pixels, but was ultimately declared "not viable" [5].

Surface deformation and alternative tactile feedback mechanisms represent significant departures from conventional pin-based displays. The Holy Braille project employs microfluidic technology to create bubbles that form dynamic tactile patterns, targeting full-page displays at \$1,000–\$2,000 — substantially more affordable than the estimated \$55,000 cost of scaling pin-based systems to comparable sizes [2]. Disney Research's TeslaTouch utilizes electrovibration to modulate friction between finger and touchscreen, creating texture perception without physical deformation, though studies indicate that the subtle tactile feedback makes complex pattern discrimination challenging for users [9].

2.1 Limitations and Design Implications

Current tactile display technologies present two critical limitations that inform our design approach for Indian educational contexts.

First, prohibitive costs — with high-resolution systems ranging from \$12,000–\$22,500 USD [9,15] — render them inaccessible to institutions serving the 90% of visually impaired students from low-income households [16]. This economic barrier extends to consumables with individual tactile diagrams (INR 290-680 per page) requiring extensive preparation time and, when multiplied across numerous concepts and students, accumulating to costs far beyond institutional budgets. This static, resource-intensive approach effectively excludes dynamic STEM visualization from curricula. The significant gap between commercial solutions and what is affordable for typical Indian schools necessitates innovative approaches to materials selection and manufacturing processes that optimize for cost while maintaining functional utility.

Second, existing solutions predominantly address biological accessibility while neglecting the crucial psychological and social dimensions of learning [6]. Most systems lack real-time content conversion capabilities, preventing synchronous classroom participation and reinforcing educational disparities. This limitation necessitates technologies that enable immediate translation of visual information into tactile representations, allowing visually impaired students to participate actively during instruction rather than accessing content retrospectively.

These interrelated limitations and their corresponding design implications have guided the following development process, informing a system architecture that balances technical capability with contextual appropriateness.

3 Design

The proposed solution explores additive manufacturing and open-source hardware principles to create a frugal tactile display system. This approach emphasizes feasibility through a phased implementation strategy, prioritizing real-time visual-to-tactile conversion with minimal latency to enable synchronous classroom participation.

3.1 System Overview

The system architecture employs a dual-component approach designed for real-time tactile feedback. The instructor-focused component captures and processes visual information from teaching surfaces, while the student-focused component provides tactile output. The implementation follows three distinct phases:

1. **Initial Prototype**: Focused on software development and limited hardware experimentation
2. **Full Grid Implementation**: Planned scaling to a complete 55 × 75 tactile array (4,125 dots)
3. **Multi-Unit Deployment**: Future support for multiple units in classroom environments

This phased approach allows for progressive validation and refinement before committing to full-scale production (Fig. 1).

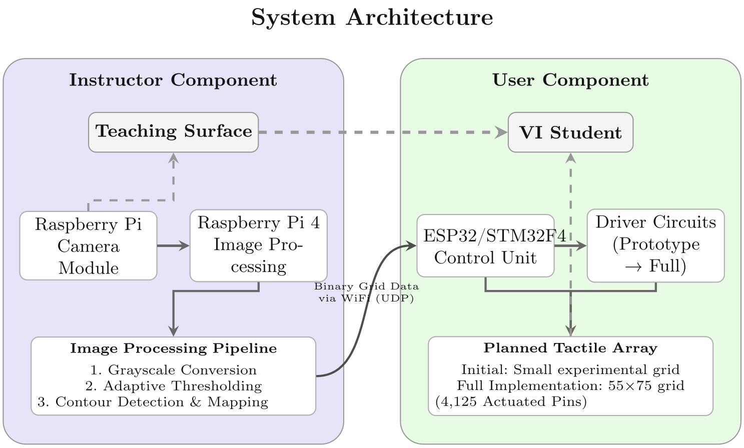

Fig. 1. Proposed dual-component system architecture showing data flow from instructor's visual content to student's tactile display. The system will evolve from initial software development to a full 55 × 75 grid implementation.

3.2 Instructor-Focused System

The instructor-focused component is designed to utilize a Raspberry Pi Camera Module connected via SPI to a Raspberry Pi 4. This configuration enables stable image capture at 320 × 240 resolution, balancing detail and processing requirements. The Raspberry Pi 4 will be equipped with a TP-Link AC600 dual-band

USB WiFi adapter configured to create a dedicated access point for wireless communication with the tactile display.

The software pipeline (Fig. 2) transforms visual input into tactile output commands through multiple stages. A Python script continuously processes camera input at approximately 5 frames per second. Each captured frame undergoes preprocessing through grayscale conversion, adaptive thresholding, and contour detection using OpenCV's findContours algorithm to identify meaningful visual elements.

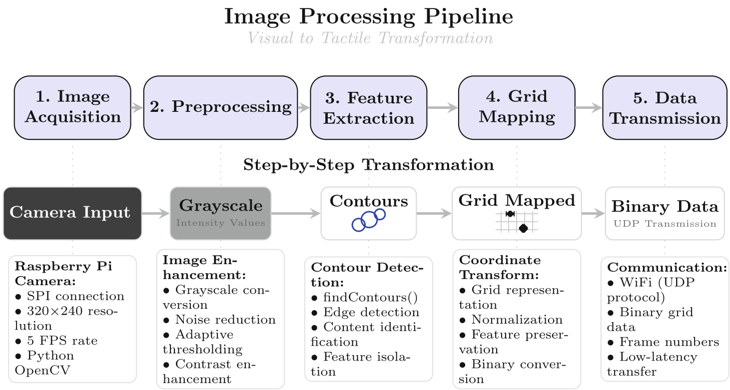

Fig. 2. Image processing pipeline for visual-to-tactile transformation. The system captures images from a Raspberry Pi Camera (1), applies preprocessing with grayscale conversion (2), extracts features using contour detection (3), maps features to a binary grid (4), and transmits binary data via WiFi using UDP protocol (5).

The detected contours are mapped to a grid corresponding to the tactile display dimensions, and the processed image is converted into a binary array where each element represents a single tactile dot. The current implementation focuses on the processing pipeline and visualization, with the data transmission protocol still under development. We are exploring UDP for wireless transmission due to its low latency characteristics, but this aspect of the system remains a work in progress.

3.3 User-Focused System

The user-focused component has distinct implementation phases:

Initial Prototype Phase : The current focus is on software development with plans to experiment with a limited number of actuated dots controlled by an ESP32 microcontroller. This experimental phase will help validate the core actuation concepts and wireless communication protocols before committing to the full system implementation.

Planned Full Implementation : For the complete 55 × 75 tactile array (4,125 dots), the system will transition to an STM32F4 microcontroller with enhanced processing capabilities and I/O handling. An ESP8266 WiFi module connected to the STM32F4 via UART will receive data from the Raspberry Pi. The planned implementation will incorporate a multiplexed control architecture with the following subsystems:

1. **Row Selection Circuit:** 74HC138 3-to-8 decoders for sequential selection of 55 rows
2. **Column Control Circuit:** 74HC595 8-bit shift registers daisy-chained for the 75 columns
3. **H-Bridge Drivers:** MOSFET-based H-bridge circuits (IRLZ34N) for bidirectional current flow
4. **Power Distribution:** Local capacitor banks (4700 μF) to buffer peak current demands

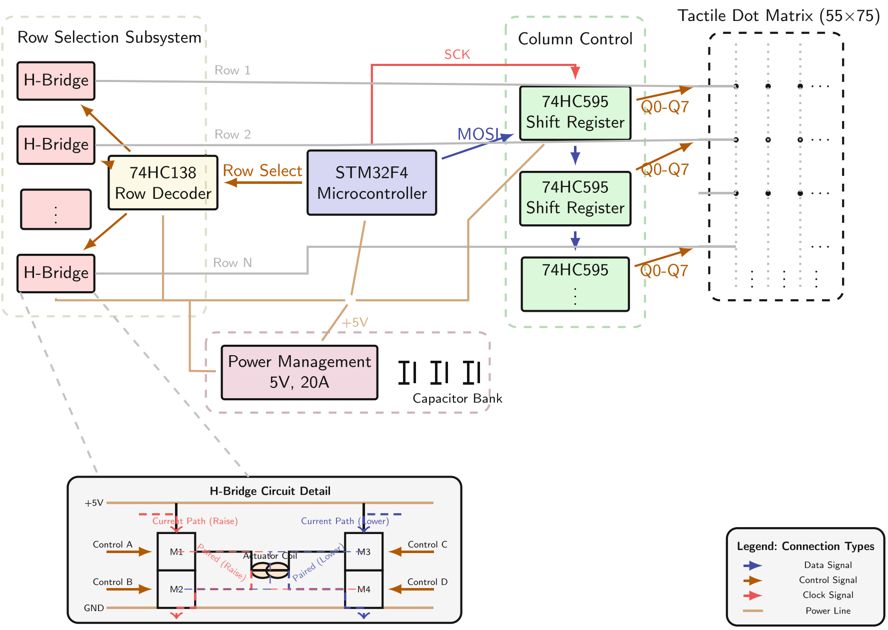

Fig. 3. Multiplexed control circuit architecture for the 55 × 75 tactile dot matrix. The system employs row-column addressing with 74HC138 decoders for row selection and cascaded 74HC595 shift registers for column control. H-bridge drivers enable bidirectional current flow, allowing dots to be both raised (red current path) and lowered (blue current path) through polarity reversal. A 4700µF capacitor bank provides current buffering during actuation events, reducing power suppl (Color figure online)y loading and voltage fluctuations. This architecture enables efficient control of 4,125 individual tactile elements with minimal component count.

The planned row-scanning approach will allow for scalable control with reasonable component count, adaptable refresh rates, and inherent fault isolation. For actuation control, a two-phase pulse-width modulation profile is designed: an initial high-current pulse (estimated at 25–30 mA per actuator based on similar designs) followed by a lower holding current (18–22 mA) until the bistable mechanism engages (Fig. 3).

3.4 Technical Specification

For the full 55 × 75 implementation, the electromagnetic actuation system will employ bistable mechanical cams that maintain dot positions without continuous power. Based on similar electromagnetic actuator designs, each actuator is estimated to require approximately 20mA during activation, yielding a calculated momentary current requirement of:

$$I_{\text{row}} = 75 \text{ dots} \times 20\text{mA/dot} = 1.5\text{A}$$

The system is designed with dual voltage requirements: 5V DC for actuators and 3.3V DC for microcontrollers. For portable operation using a 10,000mAh lithium-polymer battery, we estimate average current draw assuming 10% of dots (413) change state each cycle:

$$I_{\text{avg}} = (413 \text{ dots} \times 20\text{mA} \times \frac{50\text{ms}}{100\text{ms}}) + 250\text{mA} = 663\text{mA}$$

This yields a theoretical runtime of approximately 15.1 h, with practical runtime projected at 6–8 hours. These estimates will be validated during prototype testing and refined for the full implementation.

3.5 Cost Analysis

This section evaluates the economic viability of the tactile display system, comparing prototype and bulk production costs against commercial alternatives (Table 1).

The prototype costs are based on current market prices from US vendors. Bulk production (1,000+ units) reduces per-unit cost by 30.9% compared to prototype costs. Both prototype ($3,470) and bulk production ($2,398.75) costs represent substantial savings (70–80%) compared to commercial alternatives ($12,000–$22,500), making the system viable for deployment in resource-constrained educational environments once fully developed.

4 Current Implementation Status

This section details the developmental approach and current implementation status of our tactile display system. Our methodology combines software development for visual processing and hardware prototyping for tactile feedback, with an emphasis on iterative testing and refinement.

Table 1. System Cost Breakdown

Component	Prototype Cost ($)	Bulk Cost* ($)
Current Software Prototype		
Raspberry Pi 4 (4GB)	55.00	45.00
Raspberry Pi Camera Module V2	25.00	18.00
TP-Link AC600 USB WiFi Adapter	12.99	9.75
ESP32 Development Board	8.00	5.50
SD Card (32GB)	7.50	4.50
Power Supplies	15.00	11.00
Current Prototype Subtotal	123.49	93.75
Planned Full Implementation		
STM32F4 Microcontroller	5.00	3.50
ESP8266 WiFi Module	4.50	2.75
74HC138 Row Decoders (8)	6.40	3.60
74HC595 Shift Registers (10)	4.00	2.50
MOSFET Drivers (IRLZ34N) (55)	27.50	16.50
Passive Components	5.00	3.50
Custom Control PCB	20.00	8.00
Power Supply (5V 20A)	25.00	16.00
Control System Subtotal	97.40	56.35
Tactile Dot Grid (4,125 dots at $0.82/$0.55 per dot)	3,382.50	2,348.75
Total Planned System Cost	**3,603.39**	**2,498.85**

* Bulk production cost based on 1,000+ units

4.1 Software Development

The software component of our system follows a pipeline architecture that transforms visual input into a binary representation suitable for tactile display. The complete implementation is available on our GitHub repository[1].

Our visual processing pipeline consists of four sequential stages. The image acquisition stage captures frames from a camera focused on the instructor's writing surface. The contour detection stage processes each frame through grayscale conversion, binary thresholding for foreground-background segmentation, and edge detection using OpenCV's `findContours` algorithm (Fig. 4).

The grid mapping stage projects detected contours onto a binary grid corresponding to the tactile display dimensions (55 × 75). The binary representation stage converts the mapped grid to a binary array where each cell contains a value indicating whether the corresponding tactile dot should be raised (1) or lowered (0).

[1] https://github.com/VaaneeTripathi/refreshable-tactile-dot-grid.

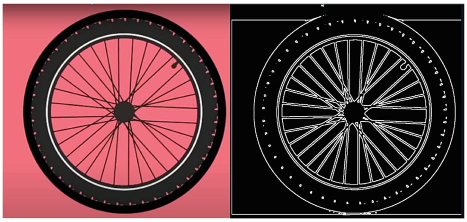

Fig. 4. A sample from the contour detection algorithm's output video

For verification, we developed a Pygame visualization tool that renders processed data as a grid of black and white cells, and an LED matrix testing platform that validates the end-to-end processing pipeline before investing in more complex tactile actuation hardware.

4.2 Hardware Design Status

A working prototype has been developed of a single tactile dot actuator inspired by Vijay's award-winning Hackaday project from 2023[2]. The design employs a miniature electromagnetic solenoid providing actuation force, a bistable mechanical cam that maintains position without continuous power, and a 3D-printed housing that integrates these components in a compact form factor. Initial testing confirms that the design provides sufficient tactile feedback while maintaining the low power consumption necessary for a battery-operated device (Fig. 5).

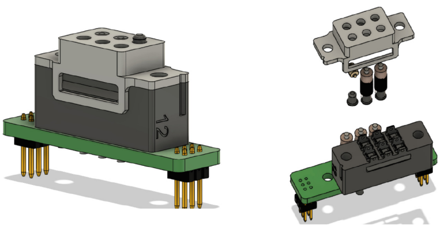

Fig. 5. The design from Vijay's Hackaday project that has served as an inspiration for this work

Current hardware development efforts focus on miniaturization of the actuator design using SLA(stereolithography) 3D printing to achieve the density required for the full 55 × 75 grid. We are sourcing components for mass production with emphasis on cost-effective alternatives to commercial parts, designing the multiplexed control circuitry for row-column addressing, and developing a scalable power distribution system.

[2] https://hackaday.io/project/191181-electromechanical-refreshable-braille-module.

5 Limitations

While the proposed tactile display system addresses several critical limitations of existing solutions, it faces notable constraints. Despite being significantly less expensive than commercial alternatives, our projected cost would still remain accessible primarily to tier-two institutions with moderate technology budgets. Although emphasizing locally available components, certain critical elements, particularly electromagnetic actuators and specialized driver ICs, must be sourced from limited suppliers with availability varying significantly across India. Urban centers offer relatively reliable access, but institutions in rural areas may face procurement challenges, potentially creating maintenance dependencies on better-resourced technical hubs.

Regarding efficacy, the system's 55×75 resolution and binary state representation have limitations in conveying complex mathematical notation, detailed scientific diagrams, and multi-series graphs. These constraints indicate that teachers must adapt their instructional approaches, potentially limiting seamless integration into existing practices.

The design also makes operational assumptions that may not hold universally: instructors must confine writing to the camera's field of view, adequate lighting and contrast are necessary, handwriting legibility impacts processing accuracy, and the current implementation lacks robust error correction for misalignment. These factors necessitate careful implementation planning and user training, highlighting areas for improvement in future iterations to enhance robustness across diverse educational environments.

6 Future Work

The current implementation represents the initial phase of a more comprehensive development roadmap. Future work will focus on prototype building and refinement, expanded functionality, and rigorous validation to ensure the system effectively meets the needs of visually impaired students in diverse educational contexts.

The immediate focus will be constructing a fully functional prototype of the complete 55×75 tactile display. We will develop optimized methods for producing the tactile cells using SLA 3D printing and injection molding techniques with custom assembly procedures. A modular physical architecture will divide the tactile array into replaceable 5×15 dot subunits, simplifying maintenance by allowing partial replacement when individual cells fail. Power management will be refined through advanced PWM control algorithms that sequence dot actuation to distribute power demands more evenly. An ergonomic, durable enclosure will incorporate angled reading surfaces, integrated palm rests, and strategic control button placement based on user feedback.

To rigorously evaluate system effectiveness, we will develop a comprehensive testing framework encompassing both technical performance validation and educational outcome assessment. Technical performance metrics will quantify end-to-end latency, contour detection accuracy, tactile dot reliability, battery life, and thermal performance. Controlled comparative studies will assess student comprehension when taught using traditional verbal description, pre-prepared tactile graphics, and our real-time system. Throughout testing, a continuous feedback loop will inform design modifications, ensuring the final system addresses practical needs identified during real-world use.

This validation framework prioritizes measuring improved educational outcomes and classroom participation rather than merely technical performance, ensuring the system delivers meaningful benefits to visually impaired students.

7 Conclusion

The development of this real-time tactile display system for visually impaired students in Indian educational contexts represents a meaningful contribution to accessibility technology while exposing significant challenges that warrant ongoing consideration. By achieving a substantial cost reduction compared to commercial alternatives, the system addresses economic barriers that have historically limited access to tactile graphics in resource-constrained environments.

However, the design's effectiveness remains contingent upon several factors requiring further investigation, including the tactile resolution's adequacy for complex STEM content, geographic disparities in component availability, and the system's integration into diverse teaching methodologies. The preliminary implementation demonstrates technical feasibility while acknowledging limitations in conveying information density equivalent to visual displays.

This tension between accessibility and functional completeness highlights the broader challenge in assistive technology development — balancing immediate practical solutions with aspirational goals of full educational equity. Future work must rigorously evaluate whether the compromises made for affordability adequately serve the educational needs of visually impaired students, particularly in understanding sophisticated mathematical and scientific concepts that rely heavily on spatial relationships and complex visual representations.

Acknowledgments. This research was supported by the **Mphasis F1 Foundation**, whose generous financial assistance made this work possible. The author expresses sincere appreciation to **Ashoka University** for providing institutional resources and academic guidance, as well as to the **Makerspace team** for their invaluable mentorship and technical expertise throughout the development process. Additionally, the author extends deep gratitude to **Deepraj Pandey**, for his unwavering support, guidance, and mentorship, as well as for his intellectual and personal encouragement throughout this endeavor. Finally, the author is profoundly grateful to their family, both given and chosen, for their unwavering support, patience, and encouragement, which have been instrumental in the successful completion of this work.

Disclosure of Interests. The authors declare no conflicts of interest.

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