MagnePins: A Modular, Affordable, and DIY Refreshable Braille and Tactile Display

Jim Smiley
Department of Human-Centred Computing
Monash University
Melbourne, Victoria, Australia
jim.smiley@monash.edu

Swamy Ananthanarayan
Department of Human-Centred Computing
Monash University
Melbourne, Victoria, Australia
Swamy.Ananthanarayan@monash.edu

Leona M Holloway
Department of Human-Centred Computing
Monash University
Melbourne, VIC, Australia
leona.holloway@monash.edu

Matthew Butler
Department of Human-Centred Computing
Monash University
Melbourne, Australia
matthew.butler@monash.edu

Tim Dwyer
Data Visualisation and Immersive Analytics
Monash University
Melbourne, VIC, Australia
tim.dwyer@monash.edu

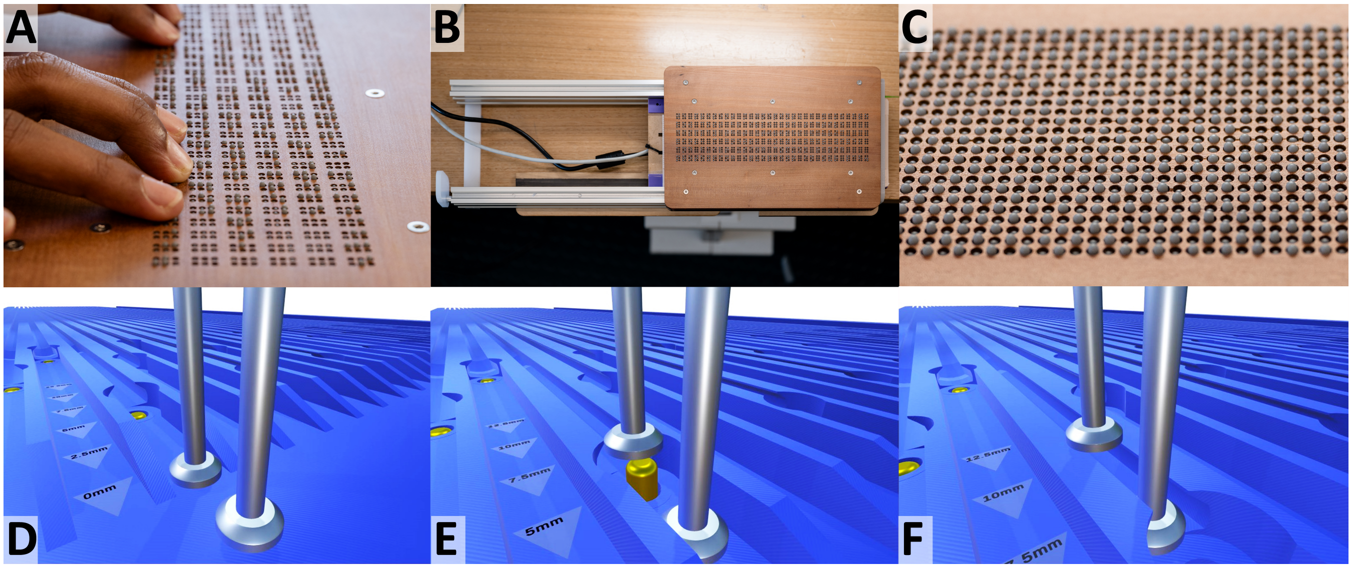


Figure 1: (A) The MagnePins braille module in use, (B) the sliding carriage fitted with the braille module, (C) the tactile module with a checkerboard test pattern. (D) A simplified timelapse of the carriage and pin locking plate as it slides underneath a passive pin array, made from fabric pins. (E) In position underneath a pin, a 15ms electromagnetic pulse fires a magnetic piston high, contacting with the pin head, and diverting it above a locking channel. (F) High and low pins locked as the carriage continues forward.

Abstract

Refreshable tactile, braille and shape changing displays have been studied in HCI for many years and have recently become commercially available. These devices offer blind and low vision users the ability to read text directly from a computer application and also the exciting possibility for increased access to dynamic tactile graphics. Commercial devices and research prototypes, however, share similar challenges and tradeoffs including cost, scalability, and miniaturisation. Research prototypes typically have either a low pin count—some only a single cell or line of braille—or a pin pitch and pin dimension far larger than the braille specification. Commercial devices that achieve both high pin count and the 2.5mm pin pitch requirement suffer from high cost, due to the inherent complexity of thousands of individual, precision, electro-mechanical or piezo actuated pins. We present 'MagnePins', an innovative, robust, and open source design that achieves a large pin array (24x89 in our prototype) with braille-compliant pin size and spacing of 2.5mm. It utilises a simple electromagnetic actuation mechanism driven

UIST '25, Busan, Republic of Korea

ACM ISBN 979-8-4007-2037-6/25/09
https://doi.org/10.1145/3746059.3747692

by reliable driver circuitry and can be fabricated economically using cheap mass-produced elements in a well-equipped makerspace. Our tests of the device indicate high accuracy (of up to 99.97%), and in testing with an expert touch reader, it provided high tactile resolution, and easy readability.

Keywords

tactile display, braille, shape changing interface

ACM Reference Format:
Jim Smiley, Swamy Ananthanarayan, Leona M Holloway, Matthew Butler, and Tim Dwyer. 2025. MagnePins: A Modular, Affordable, and DIY Refreshable Braille and Tactile Display. In *The 38th Annual ACM Symposium on User Interface Software and Technology (UIST '25), September 28–October 01, 2025, Busan, Republic of Korea.* ACM, New York, NY, USA, 12 pages. https://doi.org/10.1145/3746059.3747692

1 Introduction

Refreshable braille and tactile display technologies are improving touch access to text and graphics for blind and low vision (BLV) users. In particular, refreshable braille displays, most commonly presenting a single row of braille, are now widely used as an interface to read electronic text. More recently, larger tactile displays, such as the Graphiti [26], Monarch [2] and DotPad [12] have been developed commercially. These devices expand braille displays by increasing the number of pins and presenting them as a larger array, such as the 60×40 pins for the Dotpad, allowing the presentation of tactile refreshable graphics. However, the cost and complexity inherent in individually actuating and locking thousands of precision electromechanical pins makes these units prohibitively expensive. Indeed, units like the Monarch or Dotpad retail above $10,000 USD, and even single line braille devices are in excess of $2,000 USD. These units are also difficult to repair and replacement parts difficult to source. Typically, shipping the unit to a limited choice of niche, specialist repairers is required.

Research into refreshable tactile displays, and shape changing interfaces more generally, has long acknowledged the inherent challenges of cost, complexity, scalability and miniaturization [1]. Solutions have been developed that successfully miniaturize the moving pin and latching mechanisms [28] [20], but have either a limited pin count, and are not scaleable to larger displays, or require high precision and specialised fabrication, leading to high costs as pin count increases.

Other work takes a more simple and low cost DIY [1] approach, however does not seek or claim to meet the size and latching requirements in order to display braille or tactile graphics for the BLV community [40, 41].

In response, this work presents a low-cost, highly accurate, modular, and customisable tactile pin display, assembled from commodity components, named 'MagnePins'. Our prototype features a high pin count 24 × 89 tactile array (commensurate with commercial devices), interchangeable with a dedicated six line braille display, conforming to braille guidelines in pin spacing, latching force, and dimension. A key design principle was that the unit must be able to be fabricated and/or assembled in a well-equipped makerspace, using only off-the-shelf components and common, established digital fabrication technologies such as 3D printing, laser cutting, and basic CNC drilling/milling.

Our main contributions are:

- A novel design whereby a high resolution, passive pin array is set and latched by a sliding carriage with three staggered columns of electromagnetic pistons. This enables the use of a small number of large, less-precise, low-cost components for the same effective resolution.
- A mechanism allowing for wide tolerances, making DIY fabrication possible in a standard maker space using readily acquirable items including fabric pins, rivets, coathanger wire, and modular V-slot aluminum extrusion.
- A decoupled, modular design that allows for dedicated custom braille displays, with braille compliant pin and cell spacing, or high pin count tactile displays, with scope for larger pin counts.
- An open source design, for tactile display researchers and members of the BLV community for whom commercial displays are prohibitively expensive.
- A system using modular pin arrays that are removable in their set and locked state. This unique mechanism allows low cost, updatable braille signage, or multiple sets of tactile graphics in a classroom, each quickly set from a single unit.

2 Related Work

2.1 Background

Braille is a tactile system of reading and writing, first published by Louis Braille in 1829 [8]. Each braille cell consists of a combination of 6 dots in a 3 × 2 matrix. Within some minor variations between media and countries, braille is always produced at the same standard size to fit neatly under the finger pad [25, 29].

As the tactile equivalent of print, braille remains essential today [11] for two primary reasons. First, access to the written word is essential for children who are blind or have severe low vision to develop literacy skills. Braille provides access to spelling, punctuation and technical scripts, as well as enabling independent navigation such as scanning and comparisons [14, 31]. Secondly, adults who lose their sight later in life learn braille as a means of labeling and identifying objects that otherwise cannot be distinguished through touch, such as cans and spice jars in the kitchen, or public signage such as lift buttons and bathroom doors [30].

Touch readers, i.e. blind and low vision people who access information through touch, use both braille and tactile graphics (raised-line drawings), which are recommended whenever an image conveys important information using spatial relationships [9]. Traditionally, tactile graphics are created using methods that are labour-intensive (collage and thermoform) and/or require expensive materials and equipment (embossed graphics and swell paper diagrams). Due to these barriers, the provision of tactile graphics is generally limited to textbook materials in state-based education systems, along with the creation of maps for use in orientation and mobility training. Access to graphics for use in the workplace and at home is extremely rare.

Of great potential significance for touch readers has been the commercial availability of pin array technologies for providing

---

[1] Do It Yourself

access to text and graphics, such as refreshable braille and tactile displays. Quick access to braille renderings of electronic text is achieved through refreshable braille – most often a single line with between 16-40 braille cells. While refreshable braille displays have been widely available for several decades, it is only recently that refreshable displays capable of displaying graphics have become commercially available. The Monarch [2] and DotPad [12] are two leading examples, providing pin arrays in the order of 60 × 40 pins, which can be used to present low-resolution graphics for touch access. Excitingly, these tactile displays can facilitate the rapid delivery of touch graphics in education, work or home settings, removing one key barrier of touch graphics access. However, the inherent, high cost of manufacture means that access is mainly limited to those at well-resourced institutions.

2.2 Pin Actuation Technologies

Refreshable braille and tactile displays are an area of wide innovation, as researchers and designers grapple with the unique challenges the devices present, specifically, the scalability, miniaturisation, and cost of thousands of moving and latching pins. Bhatnagar et al. [4] and Leonardis et al. [22] provide detailed taxonomies of the various technologies that are used in current devices, prototypes, and patents. These include electromagnetics [7, 21, 36, 42], and other techniques, such as microfluidics[34], shape memory alloys[5], and electro-active polymers [3]. Piezo actuation dominates the landscape of commercial single row braille displays,[2] in that the technology is highly robust and mature. However, conventional, horizontally stacked piezo levers cannot be scaled into a densely packed, multiple line arrays. A vertical lever design overcame this limitation, allowing a 7200 pin tactile display [38], however piezo actuation remains significantly expensive. The Canute360, by the nonprofit organisation Bristol Braille is *"The World's First And Only Affordable, Multi-line Braille E-reader"* [3], and is a 360 cell, 9 line braille display. For affordability, it uses a non-piezo, mechanical approach [32], and retails for around $2,500 USD.

Precision, latching electromagnetic dots [20] are used in the new generation of commercial, multi-line displays, such as the Monarch or Dotpad [2, 12], however the complexity and precision manufacturing of thousands of individual pins is expensive.

Some prototypes address this challenge with moving gantries and a limited number of actuators. Leonardis et al. [23] use four electromagnets on a sliding carriage, which lift and adjust steel oblongs into angled slots, to present a single line of braille. However, they report an error rate of 1.1%, meaning multiple typographical errors per typical paragraph.

Chan et al. [10] mounted six piezo actuated braille cells on an xy (2-degrees of freedom cursor-style) gantry, allowing 2400 virtual taxels [4]. However, this experimental device, with a small window of focus at any one time, does not allow the lateral movement of fingertips over pins required to read braille [33], or a macro view of a tactile graphic. Moreover, it costs approx €2,000 in materials.

Other haptic technologies employ vibro-tactile feeback to convey useful information, such as the ball movement of a basketball game [5]. However, as Bhatnagar writes: *"people with visual impairment worldwide still wait for a technological breakthrough that can make full-page refreshable Braille and tactile graphics affordable"* [4].

2.3 Shape Change Interfaces in HCI Research

Tactile, pin, and haptic displays also feature more broadly in HCI research, and these research prototypes are often even more challenging, ambitious and expensive than braille and tactile pin arrays. The form factor and pin pitch is diverse, and often, the additional height dimension is important. inForm[15] and ShapeShift[35] are pin displays that can render 2.5d shapes, providing dynamic physical affordances, and can even manipulate physical objects via the changing surface, with respective pin pitches of 11mm and 7mm. Elevate [19] features 14,400 magnets, and 1200 machined plywood pins. These pins can be raised in ten discrete intervals of up to 150mm, and lock in place to create a 1.8 meter by 0.6m walkable surface to render virtual terrain. Other work has focused on the micro, rather than the macro. Haptic Edge [18] uses an array of piezo actuated pins mounted on the side of portable devices to create tactile input and output. Magtics [28] develops a miniaturised electromagnet latching dot, and a flexible wearable with dots at a 1.7cm pitch to provide tactile information.

However, most of these prototype devices are built in order to explore the novel interaction affordances that these devices offer, and tend to be complex, expensive to build, and impractical outside a lab setting.

Early work to address building practical toolkits for shape changing displays includes a modular prototyping device, Shapeclip [16]. It is a linear actuating 'shape-pixel', of which multiple units can be arranged on a screen, with their 60mm of travel controlled by the brightness of the pixels underneath, allowing researchers to *"remove complexity from the process of building shape-changing displays and re-focus effort on design of applications rather than engineering"*.

This goal is further articulated and expanded in a recent review of 'grand challenges' in shape-changing interface research [1] which calls for toolkits *"to dramatically lower the barrier to implementation"*. It also notes that *"most dissemination venues favour novelty and unique one-off prototypes"* , and stresses the need for smaller form factors and higher resolutions.

This call to action has inspired new research into practical fabrication, and toolkits for researchers in shape changing displays. Recent work by Yasu [39, 40] develops and presents novel, simple DIY workflows, ultilising pre-magnetised sheets and levitating pot magnets, in order to create pin based interactive kinetic displays. Magneswift [41], expands the number of pins at low cost, and adds a drawing surface that is then rendered on the kinetic display, however these pins do not latch, and cannot be read by touch readers. Our work is inspired by these new lines of research and explores practical fabrication of a domain specific latching pin display that can more broadly be categorised as a shape changing interface.

2.4 Do It Yourself, and DIY in Assistive and Accessible Technologies

DIY has a long heritage in electronics, computing, and audio engineering, as a solution to the high cost of equipment.

---

[2] For example: http://store.humanware.com

[3] https://bristolbraille.org/about-canute/

[4] tactile pixels

[5] e.g. One Court https://www.onecourt.io/

Assistive technology (AT) often requires unique, custom solutions tailored to the individual, and as a result, off-the-shelf solutions are often unavailable, unsuitable or highly expensive. As a matter of necessity, DIY culture thrives. Therese Willkomm, in her series of books [37], illustrates the use of modifying and improvising simple everyday items for assistive devices. Hurst and Tobias [17] coin the term Do-it-yourself Assistive Technology 'DIY-AT', and illustrate ways in which devices can be built and modified from off-the-shelf components and illustrate the potential of rapid prototyping technologies for DIY-AT.

The DIY fabrication of more complex devices, at low cost, by volunteers for others has proven to be viable, for example the E-Nable project [6] where volunteers design and build prosthetic hands, which Parry-Hill et al.[27] term "DIY-AT for Others."

Ellis et al. [13] coin the term "Bespoke AT" for ambitious projects, where "professional engineers custom build new forms of assistive technology in collaboration with the end user". Mellis et al. [24] show that in the digital age, it is even possible to DIY a device as complex as a modern cellphone. Audio engineers build advanced, professional quality studio gear from kits, and online forums [7] assist in the coordinated bulk buys of components and PCBs for economies of scale. Prototyping platforms such as Arduino, software platforms, and the ubiquity of coding education, and rapid prototyping equipment now allow any combination of the digital, analog, and mechanical.

By combining elements from these philosophies - the practical and improvisational use of inexpensive off the shelf items, DIY-AT, DIY-AT for Others, and Bespoke AT, the use of multiple, varied rapid fabrication technologies with hand crafted elements when necessary, and the potential of DIY kits, we see a potentially achievable path to a sub-$500 USD, high pin count, refreshable tactile display.

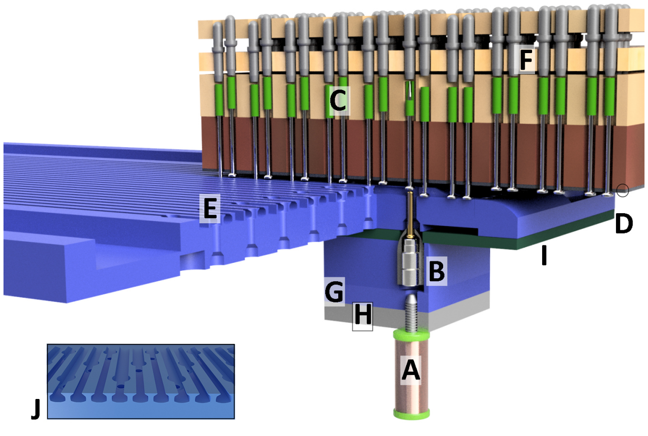


Figure 2: A cutaway view of the mechanism. Duplicated components not shown. (A) electromagnets (B) magnet and brass pistons (C) pin array (D) magnetic sheet (E) pin locking plate (F) tip module (G) air gap spacer (H) 12V buss and heatsink (I) PCB (J) An alternate, rear detail of the offset and staggered piston shafts, and pin locking profile.

3 Technical Overview

The challenges and unmet needs of refreshable braille and tactile displays are well understood, and widely acknowledged. During the iterative development, we consulted with a blind colleague - a braille and tactile display expert, to ensure readability and tactile feel.

Moreover, the strictly codified braille standard, and the well understood technical and cost limitations gave us strong constraints and objectives in which to guide our development. These included:

- *Strict adherence to readability*: This determined a 2.5mm pin spacing and 1.8mm dot diameter following the braille specification. A touch reader should not be required to learn a new method or modify their existing method.
- *DIY only*: The requirement for inexpensive and obtainable items, achievable engineering tolerances, and no outsourced specialized fabrication - only components able to be fabricated in a typical workshop or makerspace, equipped with resin and fused deposition modeling (FDM) 3D printers, a laser cutter, and CNC router.
- *Sizeable pin array*: Many single cell braille and small tactile array prototypes already exist. As such, low-cost and practical scaling to a large array is now the challenge.
- *High accuracy*: A failed pin actuation will result in a totally different character being displayed, therefore a braille display consistently displaying multiple typographical errors is considered unacceptable.
- *Faults easily diagnosable and repairable*: Technical issues must be resolvable with easily obtainable spare parts, able to be quickly installed.

Adherence to these objectives leads to our modular design - a desktop unit that measures 530mm long, 170mm deep, and 80mm high. It consists of a moving carriage on bearings, containing a precision linear encoder, an Arduino Mega, 24 electromagnets (Fig. 2A), and 24 magnet and brass piston assemblies (Fig. 2B). Above, mounted and aligned on V-slot aluminium extrusion rails, are the 2.5mm pitch, passive pin arrays (Fig. 2C). These are similar to friction based 'pin art' toys commonly seen in museum shops. Ours are made with high quality fabric pins, with vinyl collars to hold in place. As the carriage slides under each column of pins, just before the pin heads can enter triangular locking channels (Fig. 2E) the electromagnetic pistons are fired upwards with a 15ms pulse to momentarily impact and divert relevant pins high. The pin heads stick to a drilled magnetic sheet(Fig. 2D) in order to temporarily hold in place above the channels that span the length of the carriage. Resin printed tips are mounted in a sandwich of polished timber (Fig. 2F).

The electromagnets and piston assemblies are staggered and offset 7.5mm across, and 5.625mm down, in three groups of eight(Fig. 2J). Each group of electromagnets fire at 2.5mm increments, with the second and third group lagging by 2 pin columns (5mm) each. The additional 0.625mm offsets ensure separate and evenly spaced actuation times. This overlapping, staggered design is what enables the DIY approach to work - rather than attempting to miniaturise and fabricate an actuation and latching mechanism for each individual pin, the electromagnets and pot magnets are

---

[6] https://enablingthefuture.org
[7] such as www.GroupDiy.com

few, and comparatively larger and imprecise, for the same effective resolution.

Although braille can be read on evenly spaced tactile displays, the braille specification is subtly different in that the space between cells is slightly narrower, at a 3.5mm - 4.5mm pitch, rather than the 5mm of a blank column on a tactile display. Furthermore, a full 50% of pins on a tactile display are redundant when displaying braille. We built both tactile and dedicated braille arrays, illustrated in Figure 3 , with the reduced cell spacing accounted for in software. Displaying braille, while halving the number of pins, has a higher accuracy requirement, as a missing pin will change a letter or number completely, as opposed to a small gap in a tactile graphic, which may be unnoticeable.

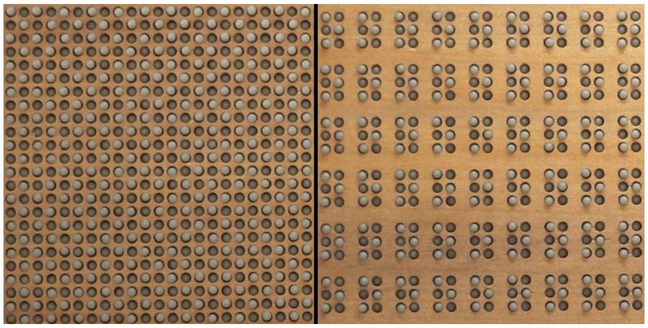


Figure 3: Our tactile module displaying a checkerboard pattern (left), compared to our braille module displaying the repeated braille letter 'o' (right)

4 Components and Fabrication

With the advent of digital fabrication technologies, Blikstein [6] warns of the dangers of 'keychain syndrome', and the trivialisation and temptations of a "*genre of tools that... have the very special property of easily generating aesthetically pleasing, almost magical products*" Rather, makerspaces should offer the potential for "*Deep engagement in projects of unprecedented complexity*". This is indeed a project of complexity, however, it is also a project of simple components, achieved by not relying on individual tools, but instead a variety of digital fabrication techniques, as well as the improvised, and hand crafted. In the subsections that follow we cover the assembly and fabrication process for the different components.

4.1 Pot Magnet and Piston Assemblies

By encasing high powered neodymium magnets with steel on three sides—in what is known as a pot magnet—the magnetic field can be concentrated, shaped and contained, in order to prevent adjacent magnets from acting on each other. The work of Zarate et al. [42], Yasu [40] and Pece et al. [28] are influential in incorporating this idea into tactile displays. In our device, instead of the tactile pin itself containing the pot magnet, as this requires duplication thousands of times for a large array, we use 24 pot magnet and brass piston assemblies, that are fired upwards to kinetically set the passive pins above.

We devised a fabrication method using 4mm diameter steel rivets, shown in Fig. 4. The mandrel is first removed, and then using wire cutters and side cutters, the rivet head is slowly chewed off, whilst crimping the rivet body into an artillery-shell like shape. The inner diameter is enlarged with a 2.78mm diameter drill, and the component is then further shaped with a drill, file, and 600 grit sandpaper. Then, a brass PCB header pin is cut under the collar, rounded at both ends, and inserted. Two 2.5mm N50 neodymium magnets, and a further 2mm N50 magnet are stacked, heatshrinked and inserted after the pin, in order to sit flush. This enables the pin free rotational movement, like a motor piston. Non-magnetic brass was chosen for the pin material,as a magnetic material will grab the pins of the display and pull them down after making contact. We still found slight magnetic interference, which caused the magnets in the middle group, surrounded on all sides, to intermittently misbehave, especially at poor alignments of the pot magnet shaft and actuator plate. Thus, we alternated the polarity of the magnets and electromagnets in this group.

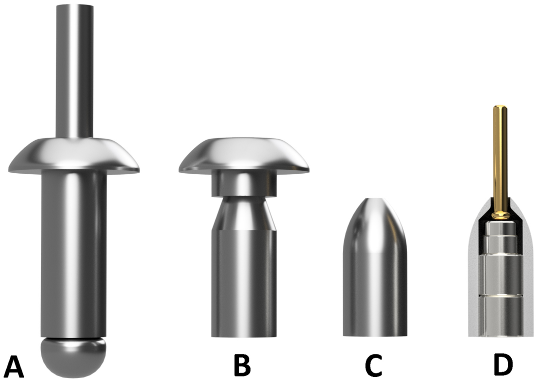


Figure 4: The rivet shaping process.(A) The mandrel is removed (B) The body is crimped (C) The body is further shaped and sanded (D) final cutaway view

4.2 Pin Modules

The pin modules (Fig. 5) consist of high quality, 16mm fabric pins, in a 24 × 89 array for our tactile module and a 6 line, 32 cell array for our braille module. After trialing various brands, we sourced a high quality box of approx 12,000 pins (500g) by Czech manufacturer Koh-I-Noor[8] The dimensional tolerances of the pins are excellent, with a random sample of 10 pins measuring from 15.96mm to 16.04 mm long, with symmetrical heads measuring between 1.37mm to 1.45mm in diameter. Extra clearance and headroom is built into our design, and larger pins, with 1.7mm heads have been confirmed to still actuate, but with reduced tolerances.

A 0.9mm magnetic sheet was drilled with 1.2mm holes, using a Roland MDX50 desktop CNC machine. In order for the magnetic fields to be consistent and strong, we perform a similar process to Magplotter [39], and use 2.5mm neodymium magnets to draw stripes with alternating polarities on either side of each column of holes. We use an analog hall effect sensor (A1326LLHLX-T, 2.5mv/G), modified to create a rudimentary gauss meter to test for consistency.

---

[8] www.kin.cz.

This sheet is then screwed around the perimeter into a 9mm MDF sheet, drilled with 0.8mm holes. The pins are inserted into these layers (Fig. 5.A), and 5mm vinyl collars, cut from wire insulation, are placed over the tips to retain (Fig. 5.B) the pins. In the case of variance in pin lengths, these collars can be raised to calibrate pin heights, however, it is advantageous that high quality pins with consistent dimensions are used instead, with the collars flush with the tips, meaning that the dots cannot be pushed lower by the user. A further 6mm MDF layer, with 2mm holes is placed on top (Fig. 5.C).

A secondary sandwich with resin printed tips (Fig. 5.D), and a sanded and oiled plywood top (Fig. 5.F), ride decoupled on top. This allows us to easily customise dot heights by simply raising the the top panel with layers of tape for precise increments. It is also designed to be easily repairable. A common failure of commercial tactile displays is that dust and dirt ingress eventually begins to jam pins. Newer devices such as the Dotpad use a plastic membrane over the surface to prevent this, but this can make it difficult for sighted educators to see what is displayed on screen when working with students, for example. Instead, we allow the top panel to be removed quickly by six screws in order to clean or replace pin tips.

Initially, we did not employ the top module and instead used a simpler assembly of resin printed tips with holes in place of the vinyl collars. However, we found that we could not repeat the tapered tiny hole diameter reliably on different batches of resin. In early iterations, acrylic sheet was used throughout, however, in consultation with a our colleague, an expert touchreader, they found the acrylic to feel unpleasant, and noticed height variance on certain rows of pins. This was found to be caused by variable thickness of up to 0.3mm across the acrylic sheet. This feedback led to the use of high quality, polished and oiled plywood instead. Another important aspect commented upon was overall dot height. Braille specifications recommend between 0.6 to 0.9mm, however, our colleague, based on their experience as a braille educator, described how students learning braille tend to require the braille dots to sit more proudly, whereas expert braille readers often prefer the dots to sit lower for greater comfort. Therefore, we make our default pin protrusion 0.9mm, which can then be customised by adding spacers underneath the top panel.

4.3 Actuator Plate and Locking Plate

The actuator and locking plates (Fig. 6) were printed on a Bambu XE1 3D printer. It prints with high dimensional accuracy, however, some drilling and post processing is required to correct shrunken hole diameters and smooth surfaces requiring low friction, in particular, the 4.3mm holes of the pot magnet shafts, the 1.2mm holes of the actuator plate, and the curved front, which collects any low-hanging pins.

The plates were originally designed as a single part, with a length at the limit of the printer's 256mm bed. Splitting the actuator and locking plates allowed for quicker iteration, as multiple iterations of the actuator plate were required, whereas the locking plate required comparatively few. This split also allows longer displays, as modular locking modules can be potentially added. An added benefit is that the locking plate can sit in place without fasteners, and once the display is set, the pin modules and locking plate can be lifted off together. Therefore, a single device can be used with multiple pin arrays and locking plates, potentially allowing multiple sets of tactile graphics to be easily produced in a classroom situation, or the rapid authoring of temporary, updateable braille signage.

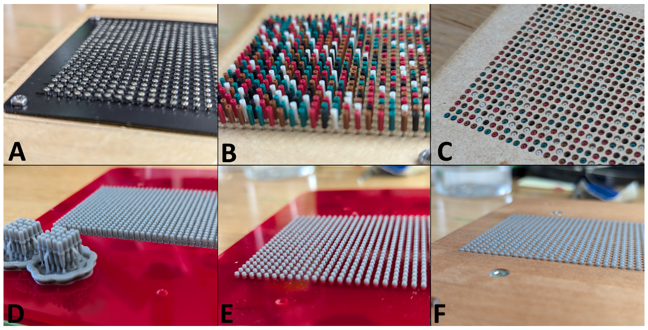


Figure 5: The pin modules. (A) Pins are inserted through a drilled magnetic sheet and an MDF layer (B) 5mm pin collars are then placed over the pin tips (C) A further drilled mdf layer is placed over these, completing the first sandwiched module. (D) Resin printed, double ended pin tips are placed in the middle of a separate sandwich. (E) The tapered ends protrude from the underside (F) A polished plywood top panel is screwed down, completing the pin tip module.

The actuator plate can be printed with optional holes for a row of magnets at the front, in order to pull all pins low and clear the display prior to actuation. This does add noise and increased resistance on the carriage. For our prototype, we elect to clear the display manually, by swiping a hand over the surface once the carriage has been retracted.

Two further small 3D printed parts are shown in Fig. 7: the pot magnet shafts, and spacer. These are screwed into brass M2.5 threaded inserts in the bottom of the actuator plate.

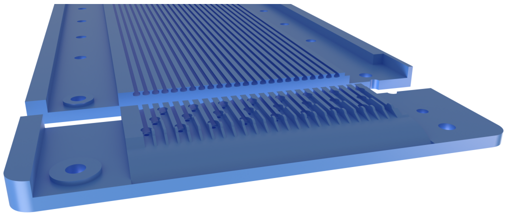


Figure 6: Actuator and locking plate

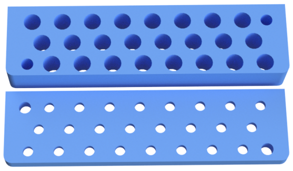


Figure 7: Pot magnet shafts and spacer

4.4 Electromagnets

These are 20mm long, and cut from coathangers, due to both the low cost and ease of sourcing, but also due to the fact that the soft, unannealed metal exhibits the best magnetic properties for our purpose, in that it has low magnetic hysteresis, and does not retain magnetism upon removal of coil current. Fig. 8 shows the fabrication process, and the finished result, which measures approx 7 – 12Ω. These are then screwed into a tapped 3mm bar of aluminium which forms the 12V buss and heatsink. The electromagnet core is therefore also at the 12V rail potential, with one end of the magnet wire having been soldered to this. The tips of the electromagnets protrude around 1.5mm, and a 3.5mm, 3d printed spacer sits between the buss plate and the pot magnets in order to provide an air gap. Otherwise, the attraction between the magnet and the steel overrides the repulsive force of the electromagnet.

The electrical connection between the threaded electromagnet and buss bar was found to be the cause of intermittent actuation failures, where multiple pin drop outs would occur in a single row. While intended to halve the number of connectors, and to provide a way of calibrating the air gap, loosening the electromagnets can lead to poor electrical connections. Future design changes are intended to address this.

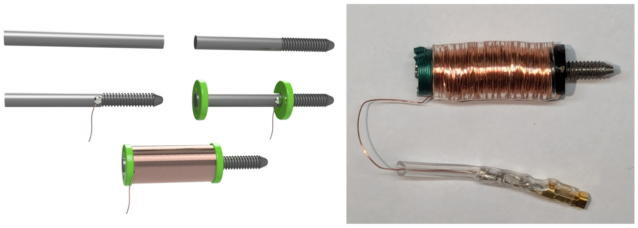


Figure 8: The electromagnet assembly process, and final result. Wire is first cut, and an end is rounded and tapped with M2 thread. 0.15mm magnet wire spool is soldered, and once cooled, 3D printed guides attached. Using a drill, the coil is tightly wound, with diameter rather than number of turns being the important aspect. Heatshrink is applied over the coil, and a header pin connector is attached.

4.5 Circuitry

The electromagnets are driven by simple FET circuits (Fig. 9), with 5ohms of resistance in series. We used IRLML2502TRPBF power mosfets, a SOT23 package, rated to 4.3 amps of continuous drain current. These are driven by an Arduiuno Mega, which mounts to our PCB, etched in our lab using a traditional UV exposure and ammonium persulphate etching tank workflow. This has proven to be quite robust, with a single FET failure over hundreds of hours of iteration and testing, including now resolved software bugs, which could leave current flowing for far longer than the 15ms duty cycle.

A design decision was made to forego an automated refresh, in favour of manually pushing the carriage. This removes bulk, and the additional cost of servo or stepper motors and driver, but it was also found that a belt driven carriage adds another layer of maintenance and source of drift and error. Maintaining consistent belt tension and calibration is a challenge, and stepper motors do not easily sense stalls. Although solutions to this do exist, and clutch mechanisms were designed and trialed, an encoder is still required in order to report position accurately in the case of skipped steps. The manual refresh, and the ability to feel the smoothness of the carriage and mechanism was found to offer a benefit outweighing the benefits of consistent speed, or the ability to pause and actuate under each column of pins. We originally used a 400 pulse per revolution optical encoder, with a 3d printed 30 tooth timing pulley and GT2 timing belt for a resolution of 0.1mm. This was replaced by an ams 5304B linear sensor on a small daughter board, with a magnetic timing strip (shown in Fig. 10).

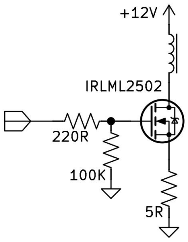


Figure 9: Electromagnet driver circuit

The encoder is read by an interrupt routine on the Arduino. Each of the three staggered electromagnet rows are treated independently in order to simplify the timing and sequencing. At each row's count of 25, minus their spacing and column offsets, the Arduino sends a 15ms pulse to the required Fet drivers and electromagnets. Eight simultaneous actuations, the maximum the stepped row design allows, momentarily draws around 8 amps of current at 12 volts. A large reservoir capacitor of 4700uf is used to smooth, allowing us to use a 12v, 6.67amp dc plugpack, although we do experience voltage drop at high speeds and pin densities.

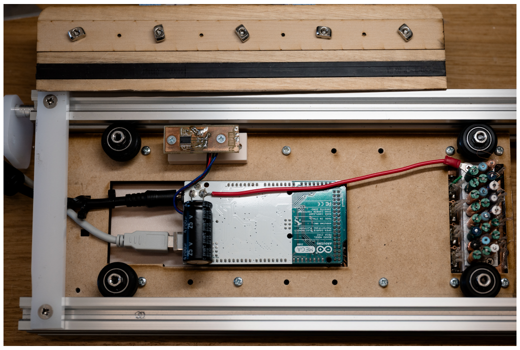
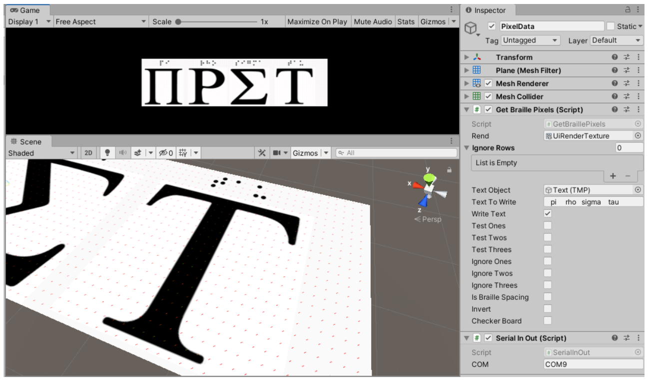


Figure 10: Underside of the device, showing Arduino, magnetic strip and encoder, filter capacitor, carriage bearings, and electromagnets

4.6 Software

A software interface was required in order to convert text to braille, and to convert braille and graphical content into a 2D binary array. For ease of prototyping, we used the Unity game engine. This was due to the robust native CSharp library to handle serial communication, ease of debugging, and the ready-made UI of the editor window, shown in Figure 11. A braille font, or graphics, are rendered on a geometric plane the same aspect ratio as our physical device. A script then uses a nested ForLoop to sample the pixel colour at even spacings of a 2d array. This is then converted to a binary string, and sent over serial to our Arduino. Our script also allows individual rows, as well as electromagnet groups, to be selected or ignored for debugging purposes.



PixelData ☑ Static ☐
Tag Untagged Layer Default

Get Braille Pixels (Script)

Script GetBraillePixels
Rend UiRenderTexture
Ignore Rows 0
List is Empty
Text Object Text (TMP)
Text To Write pi rho sigma tau
Write Text ☑
Test Ones ☐
Test Twos ☐
Test Threes ☐
Ignore Ones ☐
Ignore Twos ☐
Ignore Threes ☐
Is Braille Spacing ☐
Invert ☐
Checker Board ☐

Serial In Out (Script)

Script SerialInOut
COM COM9

Figure 11: A screenshot of the Unity Editor window. The red dots indicate where a pixel colour has been sampled to determine a high or low pin.

4.7 Cost

We do not provide a full accounting of our bill of materials cost, as certain parts, such as the wire insulation collars, or coathanger wire, are either negligible, or stocked workshop consumables (e.g., filament, resin, timber). We also rely on crucial tools and equipment as already being a part of our workshop. Further work will examine the streamlined processes and the amount of labour required to fabricate a unit, however, we can safely say that the cost of materials is in the hundreds of dollars range, rather than the thousands for a single line piezo display, or tens of thousands for a full electromechanical array. The main off the shelf components, not including shipping, and their pricing are shown in the following table, all converted to USD:

Component	Quantity	Price	Total
IRLML2502TRPBF	24	0.17	4.08
500g box of pins	1	17.36	17.36
aluminium rails	2	7.20	14.40
v-wheel bearing kit	4	3.78	15.12
ams5304B	1	10.26	10.26
300mm magnetic linear tape	1	24.00	24.00
magnet sheet	1	4.10	4.10
neodymium magnets	72	0.24	16.8
Arduino Mega	1	48.00	48.00
12v, 6.67A DC power supply	1	34.20	34.20
double sided UV sensitised pcb	1	19.53	19.53
4mm steel rivets x100	1	6.40	6.40
0.15mm magnet wire spool	1	17.70	17.70
Total			$231.95 USD

5 Evaluation

5.1 Tactile module test

We measured the accuracy and refresh rate of the full tactile module, an array of 24×89 pins with even 2.5mm spacing. Prior to the test, a design flaw was discovered, with the M2 screws around the perimeter of the magnetic sheet proving insufficient to stop the middle of the sheet from sagging, pulled down by the extra pin heads, and the elasticity from the extra holes. This sagging would intermittently lift pins in the middle rows, leading to false actuations. Future iterations of the device will glue the magnetic sheet in place, prior to drilling. However, rather than rebuilding our prototype tactile module from scratch, we sacrificed 3 pins in the middle row, pushing the collars down to lock these pins high. This now holds the magnetic sheet firmly in place, at the expense of these three locked pins. These are removed from the total pin count.

5 patterns (Fig. 12) were tested, cycling through 5 times each, in one continuous session, filmed, frames extracted and errors counted. The patterns were chosen in order for all pins to experience both states an equal number of times, for errors to be easily spotted, and to stress test the current draw and heat dissipation of the electromagnets, with actuated pin densities far greater than that found in typical tactile graphics.

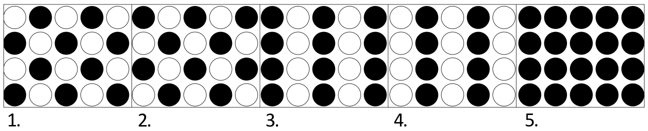


Figure 12: Test patterns: checkerboard, inverted checkerboard, columns, inverted columns, and all pins high.

Pattern	Total Errors	Avg Refresh	Accuracy
checker	4	12.6	99.96%
!checker	0	13.1	100%
column	5	12.68	99.95%
!column	3	12.61	99.97%
all high	3	13.43	99.97%
total	15/53,325	12.88s	99.97%

We calculate the accuracy rate by counting all pins, minus the three sacrificial pins, for a total of 25×2,136, even though in four of the five patterns, only half the pins are actuated. This is due to the fact that we consider false highs as valid errors, along with the false lows. In our test, we detected six false highs and nine false lows. Of the nine failed pins, four of these occur on row nineteen, and three on row seven, leading us to suspect either slightly intermittent connections on these two electromagnets, or pot magnets out of tolerance.

5.2 Braille render test

Four repeating braille characters were chosen: l, w, o, and q, (⠇ ⠺ ⠕ ⠟) to provide pin densities more challenging than typical braille sentences, where there is often only one or two dots within cells. It ensured that all pins would experience both states, as well as repeated pins, first column only, and second column only. By using repeated characters, it is easy to spot errors.

We filmed a continuous test, of the 4 repeating letters, 5 times each, paused to adjust lighting, and filmed another continuous test, for a total of 46,080 pins.

Total Errors	Avg Refresh	Accuracy
27/46080	8.03s	99.94%

This test resulted in 27 errors, more than our tactile module, despite the reduced number of pins, and the increased accuracy requirement of braille. However, these errors were entirely limited to two adjacent pins of the top line of a single braille cell, either of which would fail to actuate, and in two cases on ⠟, both failed. This began to appear intermittently during the first set of five and was rectified by replacing the pin tips, where resin printing supports were not sufficiently removed.

5.3 Refresh Rate

Because we use a manual carriage – as opposed to a stepper motor and belt drive, or linear actuator – refresh rate is determined by the user's rhythm and the feel of the machine. Excessive speed or poor alignment tend to cause grabs of the carriage, prompting the user to reverse the carriage slightly before continuing. This provides immediate tactile feedback as to the calibration, alignment, and optimal refresh rate of the device. The refresh rates shown in our tables provide an indicator of the smoothness of the run. For reference, a smooth but conservative run is around 10-12 seconds, or 20 - 24mm per second. More reckless speeds have achieved smooth and error free runs of the checkerboard pattern as fast as 7.5 seconds, or 32 mm per second, however, this is not consistently achievable, and further optimization is needed before this is recommended, as the heat generated by the electromagnets if working constantly at this speed can begin to warp 3D printed parts and stress the electromagnets and driver circuitry.

5.4 Mechanical Timing and Alignment

In order to further explore the behavior of the mechanism, We filmed the moving carriage, in slow motion, at 1000FPS. The pin modules were left off in order to view the piston timing consistency, over 5 actuations of each pin group. We analysed the footage frame by frame in order to identify when each piston is at its highest point, and the results are shown in Fig. 13. Row 19 is a clear outlier - it is much slower and more inconsistent than all others in group 3. It also aligns with the results of the tactile test, where the majority of errors were in this row. In our braille test, errors were instead localised to two pins on row 18. This row, in pin group 1, is also a slow outlier.

Pin group 3 has the largest timing variance, with a 12ms gap between the fastest and slowest magnets in the group. At our average tactile refresh rate of 18.63mm/sec however, our carriage has only moved 0.428mm in this time, still allowing plenty of headroom for contact to the 1.4mm pin head, if the pin module is correctly aligned. With our faster braille refresh of 29.88mm/sec, the carriage has moved 0.687mm, still well within tolerances.

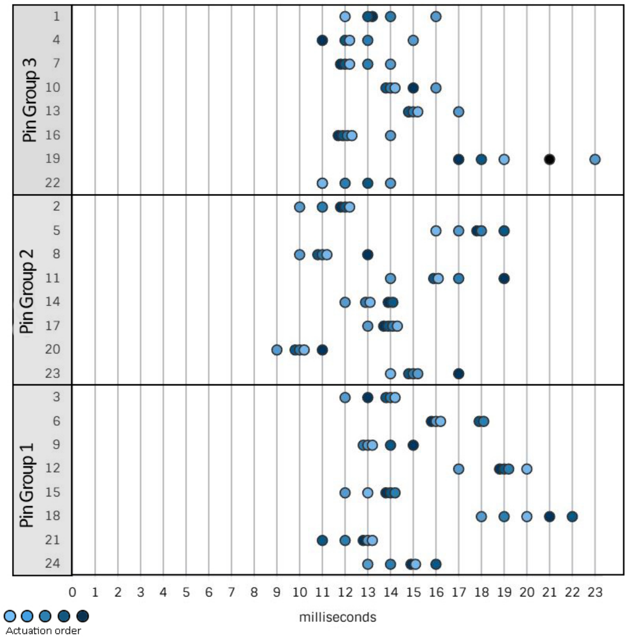


Figure 13: Magnet apogee times

At higher speeds, or the pin module sitting too far forward, the pot magnet may still actuate the pin, but deliver a glancing blow closer to the back, and fail to retract in time to avoid contacting the next pin head, causing a grab. With a swift but light touch actuating the carriage, this does not damage the contacted pin, and signals to the user to reverse slightly and continue.

By removing these outliers, and tightening the groupings, we will be able to improve our refresh rates and accuracy. A short test was carried out to confirm this, with the six slow outlier rows disabled in software, and the All Pins High pattern (13.43s average) of the tactile test repeated. This resulted in a refresh time of around 8 seconds. Reducing the pulse width to 10ms began to introduce errors, without any further improvement in the refresh rate.

Future firmware iterations are intended to add a speed offset to the actuation points - delaying at slower speeds, and bringing forward at faster speeds. However, physical tolerances must first be further tightened and improved. To achieve our baseline accuracy and refresh rates, the pin module alignment was the most important variable to calibrate. Using sheets of paper to bring forward by fractions of millimeters, or adjusting the zero stop of the carriage back, the system was setup so that the brass piston would contact the pin heads cleanly toward their front for very slow speeds, but still allowing the headroom for clean contact all the way up to our fastest refresh times.

5.5 Design Feedback

Throughout the development, informal guidance and feedback was sought at various stages from our lab colleague, a skilled touchreader and tactile display expert who is blind. Changes were made directly as a result of this feedback, such as ensuring highly consistent and customisable dot heights, and material choice for tactile feel. An informal feedback session was conducted after these changes were implemented. A list of names were used as example braille text, and were read successfully. They were also shown the planned braille test patterns, as well as a tactile graphic with 4 letters from the Greek alphabet, as shown in Fig. 14. It was reported that "The braille is easy to read. The dots are good, they're nice to feel" and it is "not too noisy". "The panel feels nice... We talked some time ago about material, and this one feels nice and smooth."

The tactile graphic was informative, and small details were able to be noticed. "The number of rows here, the resolution...I'm able to get a good concept of what it is, including the font type, with the serifs."

It also highlighted the value of tactile access to the many print graphics that are currently not available to BLV people.

> "Pi - is that correct, that it is like two pillars with a crossbar? I did not know what pi looked like. I've learned something. Rho is like a capital P? Ah, this is fun, you learn something every day."

The manual refresh took some time and practice in order to get a smooth and reasonable refresh rate, especially as at this point the display was not as calibrated and optimised as in our tests. By the end of the session, they were achieving refresh rates around 14 seconds. "It does go smoothly - but it requires a lot of dexterity and concentration."

There was no preference between reading braille on either module, and the reduced column spacing difference was not noticed. This may mean that the reduced 4.5mm braille spacing can instead be made consistent with the tactile module, simplifying software and assembly.

They also suggested a software option in order to invert the display for right or left hand actuation.

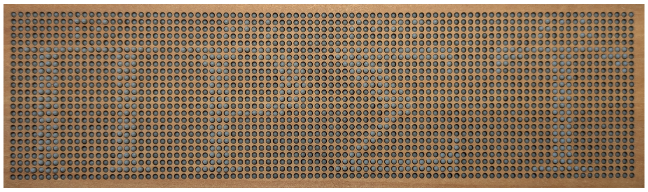


Figure 14: A tactile graphic, displayed on our device, showing the Greek letters pi, rho, sigma and tau, with the names given in braille above each. Tactile graphic modified from the APH tactile graphic library.

6 Limitations and Future Work

While advances in shape-shifting research and commercial refreshable braille displays have relied on advanced manufacture and exotic material techniques, our prototype is developed with a practical and pragmatic approach, relying on improvisational use of readily available and low-cost materials. We expect there is room for future work to theoretically model and optimise the design and behaviour of the device. As with most innovations that seek to dramatically lower costs, limitations and trade-offs exist.

6.1 Inherent Tradeoffs

Due to the locking plate, the width of the unit must be at least twice the width of the display itself, and the area above the extended carriage is currently redundant space. We plan to fill this area with a braille keyboard. The unit is bulky, with a width of 530mm, and is a desktop unit, rather than a portable design.

Our sliding carriage design does not allow pins to be individually addressed and actuated - the carriage needs to travel the full width of the display in order to refresh. This rules out certain features that more expensive tactile displays possess, such as blinking cursors.

Our mechanism will grab pins if the carriage travels too fast, or the pin module is misaligned. Consequently, we made the design decision to manually push the carriage to mitigate potential pinlocks. However, steady and smooth carriage movement requires some training.

6.2 The DIY Approach

While we will continue to refine and innovate working towards a ready-to-assemble kit-form, we are open-sourcing all our designs to enable a community of makers and researchers with an interest in supporting the BLV community. Our design files, and diy tutorials are available in a public Github repository [9] and encourage those interested to build their own devices.

Although we achieved high levels of accuracy, some calibration is still required. We still need to establish processes for consistent calibration and quality control. At the moment, makers can attempt assembly in stages, beginning with fewer lines of braille to get insight into the required accuracy, and troubleshooting processes, before the larger array is filled out. Importantly, we would still recommend commercial products such as the Dotpad and Monarch for individuals and organisations that can afford them.

We were dogmatic in our DIY-only approach when iterating the device. This leads to some tedious processes, such as the cutting of vinyl collars, and the fabrication of pot magnet bodies. An amount of custom manufacturing may offer higher quality results, and remove inefficient processes, without compromising the project ethos, however, further exploration is required.

6.3 Design Improvements

Despite the high accuracy, our prototype can be further improved, with tighter tolerances. Future work will seek to update, standardize components, and streamline or eliminate processes. Planned changes include:

Increasing the electromagnet row spacing from 5.625mm to 8.33mm. This will allow an increased electromagnet diameter of up to 7.5mm, as well as reducing remaining magnetic interference between pot magnets, and allowing consistent magnetic polarities.

This redesign will allow us to optimize the buss bar and electromagnet connections, by replacing aluminium with brass, and more precisely align the piston shafts with the actuator plate. Teflon inserts, or acetal can also potentially reduce friction.

Codified, simple and efficient calibration procedures, and low cost diagnostic sensors and jigs. The use of 1000fps slow motion filming

---

[9] https://github.com/JimSmiley/Magnepins

has been highly useful in troubleshooting our prototype and viewing pin behaviour. Potentially the 240fps available on smartphones, in tandem with an etched transparent calibration sheet can be used to view actuation points and timing.

7 Conclusion

In this paper, we present MagnePins - a modular braille and refreshable tactile display, with a 2.5mm pin pitch, and high-pin count, that can be DIY fabricated at low cost. To achieve this, we combine a modular assembly of electromagnetic components driven by a manual sliding carriage. This novel mechanism eliminates the need for high precision custom fabrication, and instead, uses improvised low cost components. We achieve high accuracy in displaying braille and tactile graphics, and received positive feedback in a preliminary evaluation with a blind user. We identify additional improvements, such as increased electromagnet row spacing to support a faster refresh rate, in future work. We encourage others to use the information we provide to build and modify their own versions of these devices, in order to assist the BLV community to access tactile graphics and braille, and also to lower the barrier for researchers in this field.

References

[1] Jason Alexander, Anne Roudaut, Jürgen Steimle, Kasper Hornbæk, Miguel Bruns Alonso, Sean Follmer, and Timothy Merritt. 2018. Grand Challenges in Shape-Changing Interface Research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–14. doi:10.1145/3173574.3173873

[2] American Printing House for the Blind. 2025. *Meet Monarch.* https://www.aph.org/meet-monarch/

[3] Nadine Besse, Samuel Rosset, Juan José Zárate, Elisabetta Ferrari, Luca Brayda, and Herbert Shea. 2018. Understanding Graphics on a Scalable Latching Assistive Haptic Display Using a Shape Memory Polymer Membrane. *IEEE Transactions on Haptics* 11, 1 (2018), 30–38. doi:10.1109/TOH.2017.2767049

[4] Tigmanshu Bhatnagar, Albert Higgins, Nicolai Marquardt, Mark Miodownik, and Catherine Holloway. 2023. Analysis of Product Architectures of Pin Array Technologies for Tactile Displays. *Proceedings of the ACM on Human-Computer Interaction* 7, ISS (2023), 135–155. doi:10.1145/3626468

[5] Tigmanshu Bhatnagar, Nicolai Marquardt, Mark Miodownik, and Catherine Holloway. 2021. Transforming a Monolithic Sheet of Nitinol into a Passive Reconfigurable Tactile Pixel Array Display at Braille Resolution. In *2021 IEEE World Haptics Conference (WHC)*. 409–414. doi:10.1109/WHC49131.2021.9517239

[6] Paulo Blikstein. 2013. *Digital Fabrication and 'Making' in Education: The The Democratization of Invention.* doi:10.14361/transcript.9783839423820.203

[7] Adrian Bowles, Ahmed Rahman, Tim Jarman, Paul Morris, and Jon Gore. 2005. A new technology for high density actuator arrays. In *Smart Structures and Integrated Systems (Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 5764)*, Alison B. Flatau (Ed.). 680–689. doi:10.1117/12.598455

[8] Louis Braille. 1829. *Procédé pour écrire les Paroles, la Musique, et le Plain-chant au moyen de points (Procedure for Writing Words, Music, and Plainsong in Dots).* Répéteur à L'institution Royale des Jeunes Aveugles (Royal Institution of Blind Youth), Paris. https://nfb.org/sites/nfb.org/files/images/nfb/publications/braille/thefirstpublicationofthebraillecode.html

[9] Braille Authority of North America (BANA). 2022. *Guidelines and Standards for Tactile Graphics.* The Braille Authority of North America, USA. https://www.brailleauthority.org/guidelines-and-standards-tactile-graphics

[10] Jason Chan, Thorsten Maucher, Johannes Schemmel, Dana Kilroy, Fiona Newell, and Karlheinz Meier. 2007. The virtual haptic display: A device for exploring 2-D virtual shapes in the tactile modality. *Behavior research methods* 39 (12 2007), 802–10. doi:10.3758/BF03192972

[11] Judith Dixon. 2000. *Braille into the next millenium.* National Library Service for the Blind (NLS), Washington, D.C., USA.

[12] Dot Inc. 2022. . https://pad.dotincorp.com/

[13] Kirsten Ellis, Ross de Vent, Reuben Kirkham, and Patrick Olivier. 2020. Bespoke Reflections: Creating a One-Handed Braille Keyboard. In *Proceedings of the 22nd International ACM SIGACCESS Conference on Computers and Accessibility* (Virtual Event, Greece) *(ASSETS '20)*. Association for Computing Machinery, New York, NY, USA, Article 13, 13 pages. doi:10.1145/3373625.3417019

[14] Karen A. Erickson and Deborah Hatton. 2007. Literacy and Visual Impairment. *Seminars in Speech and Language* 28, 1 (2007). doi:10.1055/s-2007-967930

[15] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. inFORM: Dynamic physical affordances and constraints through shape and object actuation. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology* (St. Andrews, Scotland, United Kingdom) *(UIST '13)*. Association for Computing Machinery, New York, NY, USA, 417–426. doi:10.1145/2501988.2502032

[16] John Hardy, Christian Weichel, Faisal Taher, John Vidler, and Jason Alexander. 2015. ShapeClip: Towards Rapid Prototyping with Shape-Changing Displays for Designers. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 19–28. doi:10.1145/2702123.2702599

[17] Amy Hurst and Jasmine Tobias. 2011. Empowering individuals with do-it-yourself assistive technology. In *The Proceedings of the 13th International ACM SIGACCESS Conference on Computers and Accessibility* (Dundee, Scotland, UK) *(ASSETS '11)*. Association for Computing Machinery, New York, NY, USA, 11–18. doi:10.1145/2049536.2049541

[18] Sungjune Jang, Lawrence H. Kim, Kesler Tanner, Hiroshi Ishii, and Sean Follmer. 2016. Haptic Edge Display for Mobile Tactile Interaction. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 3706–3716. doi:10.1145/2858036.2858264

[19] Seungwoo Je, Hyunseung Lim, Kongpyung Moon, Shan-Yuan Teng, Jas Brooks, Pedro Lopes, and Andrea Bianchi. 2021. Elevate: A Walkable Pin-Array for Large Shape-Changing Terrains. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 127, 11 pages. doi:10.1145/3411764.3445454

[20] Joonyeong Kim, Byung-Kil Han, Dongbum Pyo, Semin Ryu, Hanbyeol Kim, and Dong-Soo Kwon. 2020. Braille Display for Portable Device Using Flip-Latch Structured Electromagnetic Actuator. *IEEE Transactions on Haptics* 13, 1 (2020), 59–65. doi:10.1109/TOH.2019.2963858

[21] Fabrizio Leo, Elena Cocchi, Elisabetta Ferrari, and Luca Brayda. 2020. *Maps as Ability Amplifiers: Using Graphical Tactile Displays to Enhance Spatial Skills in People Who Are Visually Impaired.* Springer, 65–88.

[22] Daniele Leonardis, Loconsole Claudio, and Antonio Frisoli. 2018. A survey on innovative refreshable braille display technologies. In *Advances in Design for Inclusion: Proceedings of the AHFE 2017 International Conference on Design for Inclusion* (Los Angeles, CA, USA). Springer, 488–498.

[23] Claudio Loconsole, Daniele Leonardis, M. Gabardi, and Antonio Frisoli. 2019. BrailleCursor: an Innovative Refreshable Braille Display Based on a Single Sliding Actuator and Simple Passive Pins. In *IEEE World Haptics Conference (WHC)*. IEEE, 139–144. doi:10.1109/WHC.2019.8816128

[24] David A. Mellis and Leah Buechley. 2014. Do-it-yourself cellphones: an investigation into the possibilities and limits of high-tech DIY. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI '14)*. Association for Computing Machinery, New York, NY, USA, 1723–1732. doi:10.1145/2556288.2557309

[25] National Library Service (NLS). 2008. *Specification 800: Braille Books and Pamphlets.* National Library Service for the Blind and Physically Handicapped of the Library of Congress, Washington, DC, USA.

[26] Orbit Research. 2016. *Graphiti® - a Breakthrough in Non-Visual Access to All Forms of Graphical Information.* http://www.orbitresearch.com/product/graphiti/

[27] Jeremiah Parry-Hill, Patrick C. Shih, Jennifer Mankoff, and Daniel Ashbrook. 2017. Understanding Volunteer AT Fabricators: Opportunities and Challenges in DIY-AT for Others in e-NABLE. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 6184–6194. doi:10.1145/3025453.3026045

[28] Fabrizio Pece, Juan Jose Zarate, Velko Vechev, Nadine Besse, Olexandr Gudozhnik, Herbert Shea, and Otmar Hilliges. 2017. MagTics: Flexible and Thin Form Factor Magnetic Actuators for Dynamic and Wearable Haptic Feedback. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 143–154. doi:10.1145/3126594.3126609

[29] PharmaBraille. n.d.. Pharmaceutical Braille. https://www.pharmabraille.com/pharmaceutical-braille/marburg-medium-font-standard/

[30] Paul E Ponchillia and Susan Kay Vlahas Ponchillia. 1996. *Foundations of rehabilitation teaching with persons who are blind or visually impaired.* American Foundation for the Blind, New York, NY, USA.

[31] Evelyn J. Rex, Alan J. Koenig, Diane Wormsley, and Robert L. Baker. 1994. *Foundations of Braille Literacy.* AFB Press, New York, NY, USA.

[32] Ed Rogers. 2016. Designing Canute with the blind community. https://iceb.org/gapapers16.html

[33] Alexander Russomanno, Sile O'Modhrain, R. Brent Gillespie, and Matthew W. M. Rodger. 2015. Refreshing Refreshable Braille Displays. *IEEE Transactions on Haptics* 8, 3 (2015), 287–297. doi:10.1109/TOH.2015.2423492

[34] Boxue Shan, Congying Liu, Yuan Guo, Yiheng Wang, Weidong Guo, Yuru Zhang, and Dangxiao Wang. 2024. A Multi-Layer Stacked Microfluidic Tactile Display With High Spatial Resolution. *IEEE Transactions on Haptics* 17, 4 (2024), 546–556. doi:10.1109/TOH.2024.3367708

[35] Alexa F. Siu, Eric J. Gonzalez, Shenli Yuan, Jason B. Ginsberg, and Sean Follmer. 2018. shapeShift: 2D Spatial Manipulation and Self-Actuation of Tabletop Shape Displays for Tangible and Haptic Interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–13. doi:10.1145/3173574.3173865

[36] Jeremy Streque, Abdelkrim Talbi, Philippe Pernod, and Vladimir Preobrazhensky. 2010. New Magnetic Microactuator Design Based on PDMS Elastomer and MEMS Technologies for Tactile Display. *IEEE Transactions on Haptics* 3, 2 (2010), 88–97. doi:10.1109/TOH.2009.61

[37] Therese Willkomm. 2013. *Assistive Technology Solutions in Minutes Book II - Ordinary Items Extraordinary Solutions*. Institute on Disability at The University of New Hampshire.

[38] Thorsten Völkel, Gerhard Weber, and Ulrich Baumann. 2008. Tactile Graphics Revised: The Novel BrailleDis 9000 Pin-Matrix Device with Multitouch Input. *LNCS* 5105, 835–842. doi:10.1007/978-3-540-70540-6_124

[39] Kentaro Yasu. 2017. Magnetic plotter: a macrotexture design method using magnetic rubber sheets. In *ACM SIGGRAPH 2017 Studio* (Los Angeles, California) *(SIGGRAPH '17)*. Association for Computing Machinery, New York, NY, USA, Article 6, 2 pages. doi:10.1145/3084863.3084866

[40] Kentaro Yasu. 2022. MagneShape: A Non-electrical Pin-Based Shape-Changing Display. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) *(UIST '22)*. Association for Computing Machinery, New York, NY, USA, Article 71, 12 pages. doi:10.1145/3526113.3545645

[41] Kentaro Yasu. 2024. MagneSwift: Low-Cost, Interactive Shape Display Leveraging Magnetic Materials. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 863, 11 pages. doi:10.1145/3613904.3642058

[42] Juan José Zárate and Herbert Shea. 2017. Using Pot-Magnets to Enable Stable and Scalable Electromagnetic Tactile Displays. *IEEE Transactions on Haptics* 10, 1 (2017), 106–112. doi:10.1109/TOH.2016.2591951