White Rose Research Online

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk
Universities of Leeds, Sheffield and York

Deposited via The University of York.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/id/eprint/171323/

Version: Published Version

---

**Article:**
Fletcher, Alex, Downs, Sam, Frost, William James et al. (2021) Magnetic Braille Using Ferrofluids. Journal of Physics D: Applied Physics. 215001. ISSN: 1361-6463

https://doi.org/10.1088/1361-6463/abe820

---

**Reuse**
This article is distributed under the terms of the Creative Commons Attribution (CC BY) licence. This licence allows you to distribute, remix, tweak, and build upon the work, even commercially, as long as you credit the authors for the original work. More information and the full terms of the licence here:
https://creativecommons.org/licenses/

**Takedown**
If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

Journal of Physics D: Applied Physics

**PAPER** • **OPEN ACCESS**

# Magnetic braille using ferrofluids

To cite this article: A M Fletcher *et al* 2021 *J. Phys. D: Appl. Phys.* **54** 215001

View the article online for updates and enhancements.

IOP ebooks™

Bringing together innovative digital publishing with leading authors from the global scientific community.

Start exploring the collection–download the first chapter of every title for free.

This content was downloaded from IP address 82.132.224.131 on 10/03/2021 at 15:11

OPEN ACCESS
IOP Publishing
Journal of Physics D: Applied Physics
J. Phys. D: Appl. Phys. **54** (2021) 215001 (7pp)
https://doi.org/10.1088/1361-6463/abe820

# Magnetic braille using ferrofluids

**A M Fletcher[1], J S P Downs[1], W Frost[2], D Clarke[2], K O'Grady[2] and A Hirohata[1]**

[1] Department of Electronic Engineering, University of York, Heslington, York YO10 5DD, United Kingdom
[2] Department of Physics, University of York, Heslington, York YO10 5DD, United Kingdom

E-mail: atsufumi.hirohata@york.ac.uk

Received 8 November 2020, revised 12 February 2021
Accepted for publication 19 February 2021
Published 8 March 2021

**Abstract**

Braille provides an invaluable tactile reading system for the visually impaired. However, current braille keyboards and technology are external mechanical devices limited by their large form factor, high expense and long refresh rates. A magnetic touchpad in which braille dots are formed through a ferrofluid medium is a potential device that could promise to replace current braille technology by providing higher refresh rates, lower cost and give easy integration into current devices. In this report, work is shown towards developing a proof of concept magnetic braille touch pad, wherein a braille dot is formed using a ferrofluid by a controlled magnetic field produced by a small scale electromagnet. Attempted optimisation of braille dot formation is also undertaken, varying ferrofluid properties and electromagnet architecture to form accurate braille dots. Results show that magnetic braille touch pads are realistic devices that can be built and that there are clearly extensive opportunities for further research. In the future magnetic braille touch pads could be fully implemented into information technology devices for use by the visually impaired.

Keywords: magnetic fluids, iron oxides, magnetic field

(Some figures may appear in colour only in the online journal)

## 1. Introduction

Braille is a tactile reading and writing system used by the visually impaired. Braille dots are arranged in a 2 × 3 cell which can be used to represent letters, numbers and mathematical symbols to a visually impaired person. Braille cells can then be read by touching a finger to a cell and moving left to right across multiple cells. As of 2019 over 150 million people use braille across the world [1], signifying it as an invaluable resource for the blind and visually impaired. Whilst braille is a very important tool for the visually impaired it is also limited in that its primary usage is for printed media, for example books and markings on medical packages. Braille is not typically used for modern or digital applications. Instead visually impaired people typically use a piece of screen reader/text-to-speech software to interact with the output of a computer or tablet. Input to a computer can also be carried out with speech-to-text software such as NonVisual Desktop Access [2]. An alternative to a voice activated approach is to use braille; current electronic braille hardware exists as a refreshable braille display. Refreshable braille displays are large external mechanical keyboards or terminals that output braille characters with actuated pins to match the output on the connected computer [3]. For example, Orbit Reader 20 [4] has a large size of 168 mm × 112 mm × 35.56 mm with 450 g. Such a mechanical braille is expensive, typically between $1300 and $5000 and with a long refresh time 300 ms for Orbit Reader 20.

An alternative non-mechanical refreshable magnetic braille touchpad can be fabricated with a ferrofluid as a medium controlled by magnetic fields from small scale electromagnets through which braille can be displayed and read. Tamilarasan *et al* [5] have shown the use of magnetic simulations to determine optimal electromagnet architecture, wherein no interference between electromagnets is found. They have not built a physical device but the paper suggests the potential of

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

 © 2021 The Author(s). Published by IOP Publishing Ltd Printed in the UK

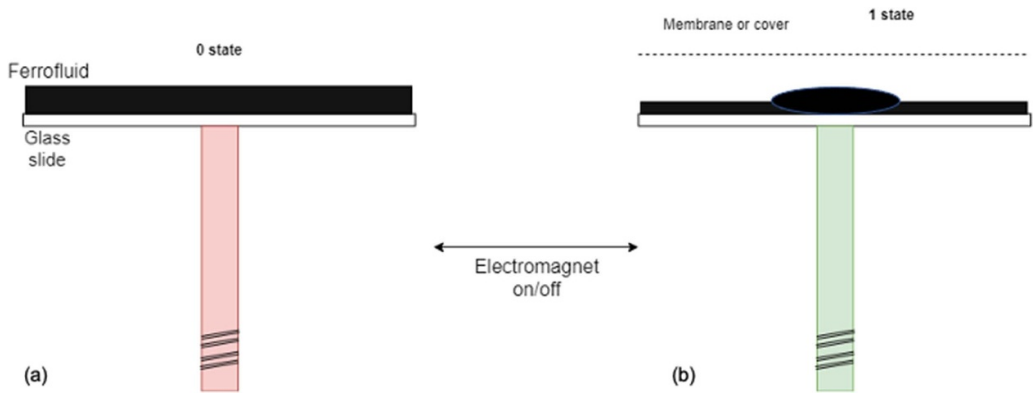


**Figure 1.** An example diagram of a single braille dot display to be designed and built during this study: (a) '0' state without an electrical current application and (b) '1' state with a current application.

magnetic braille touchpads as their design process and simulation show the consideration of electrode architecture and magnetic field strength. In this paper, we create a magnetic braille that shows proof of concept for the output of braille dots in a ferrofluid medium controlled by a magnetic field generated by an electromagnet.

In a ferrofluid, the magnetic nanoparticles (MNPs) can undergo Néel and Brownian relaxation [6]. The Néel relaxation time is given by

$$\tau_{\mathrm{N}} = \tau_0 \exp\left(KV/k_{\mathrm{B}}T\right) \tag{1}$$

where $\tau_0$: $10^{-9}$ s, $K$: magnetic anisotropy constant ($5 \times 10^4$ J m$^{-3}$ for magnetite), $V$: volume of the magnetic core of the nanoparticle, $k_{\mathrm{B}}$: Boltzmann constant and $T$: temperature), giving $\tau_{\mathrm{N}}$ at room temperature to be on or above the order of 1 ns. This relaxation process generally designated Néel relaxation, relates to the internal rotation of the magnetic moment of the single domain particles with the spins within each particle remaining parallel as the coherent reversal takes place [7]. However in a ferrofluid it is perfectly possible for particles to physically rotate in the presence of a field in addition to undergoing Néel reversal as given by equation (1). This is particularly true for the case where the particles exist as aggregates which in systems such as that used here and also a larger particle is very common. Aggregates form of particles where the surfactant coating intended to keep the particles apart is either incomplete or the particles have not been coated at all. Under these circumstances the particles come together in an attempt to form a flux closure configuration. Such aggregates can be quite large consisting of up to thousands of particles resulting in a micron size entity but are generally much smaller consisting of perhaps 5–10 particles. Nonetheless the attempt to form a flux closure configuration results in the pinning of the direction of the moment of an individual particle although in the presence of a field the aggregate will develop a net moment and hence this larger entity will attempt to follow the field by rotation of the aggregate rather than the switching of an individual particle within it. Under these circumstances the Brownian rotation relaxation time is given by

$$\tau_{\mathrm{B}} = \frac{3V_{\mathrm{H}}\eta}{k_{\mathrm{B}}T} \tag{2}$$

where $\eta$ is the viscosity of the fluid and $V_{\mathrm{H}}$ is the hydrodynamic volume of the particle or aggregate. In practice both modes of reversal are present in most samples of ferrofluid but even for the bulk rotation mechanism the relaxation time depending on the viscosity of the carrier fluid, is typically of the order of microseconds or at worst milliseconds depending upon the size of the aggregate. This allows for a high refresh rate due to a small relaxation time that could be easily integrated into information technology devices. For the nanoparticles with the diameter of 10 nm used in this study, the Néel relaxation probably dominates the rotation mechanism [8].

An example diagram of a single braille dot device is shown in figure 1. Figure 1(a) shows the off or '0' state of the braille dot. With the electromagnet switched off the ferrofluid is not affected by a magnetic field and thus lies flat. Figure 1(b) shows the on or '1' state of the braille dot. With the electromagnet switched on the ferrofluid forms a dot due to the magnetic field present at the pole of the electromagnet. To achieve a proof of concept device for the magnetic braille touchpad we have used mathematical analysis of electromagnets and ferrofluids to find appropriate magnetic field values and braille design. We have then modelled the design to optimise braille dot formation due to MNP diameters and ferrofluid density to maximise the dot diameter and definition.

## 2. Magnetic field simulations

A basic electromagnet model has been designed using the software, Finite Element Method Magnetics (FEMM) [9]. This design has been created in the axisymmetric mode and therefore only appears to be half of the full device as shown in figure 2. The model shows the ferrofluid spread on top of a 0.15 mm thick piece of glass. A microscope slide is to be used in practice, with the electromagnet directly below. A relative permeability of 2 will be used for the ferrofluid.

An initial simulation was performed to determine the difference in the magnetic field produced when the core length was changed. The electromagnet coil turns, electrical current,

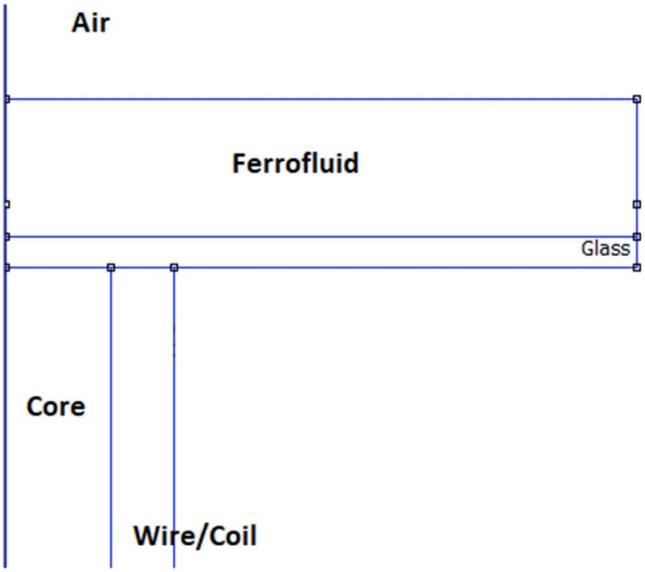


**Figure 2.** The basic electromagnet and ferrofluid model used for the simulation in FEMM. The core extends off the screen and has been cut for ease of viewing. Boundary conditions for the simulation are also not seen in this image.

core material and coil wire diameter were all selected to be as follows: 200 turns, 0.5 A current, the core to be air or a ferromagnetic material (pure Fe and Co) and the wire was 30 swg (0.315 mm in diameter). From the simulations, a 40 mm and 200 turn electromagnet with a steel core should be suitable for this study at 0.1 $\sim$ 0.5 A. At 0.5 A, the field strength at a distance of 1.2 mm from the electromagnet tip is simulated to be approximately 1.5 kA $m^{-1}$. This is sufficient to hold the ferrofluid against gravity. A typical simulation is shown in figure 3.

## 3. Magnetic braille fabrication

The ferrofluid used was made by dispersing 1.05 and 0.55 g MNPs in 5 ml hydrocarbon oil (Isopar M) with low density (0.79 kg $l^{-1}$ (0.79 g $ml^{-1}$)) and low viscosity (0.002 Pa·s (2 cP)) as a carrier fluid [10, 11]. Oleic acid coated magnetite MNPs with 10 nm diameter (Liquids Research Limited, sample 3) [12] were used for this study. These were then mixed in varying concentrations to give ferrofluids of varying properties as summarised in table 1.

Table 1 shows the properties of the ferrofluids produced by mixing oleic coated magnetite MNPs into the iso paraffin oil. Isopar-M has the advantage of being a $C_{13}$ linear chain oil which matches well to the chain length of the oleic acid. This leads to an almost ideal dispersion subject to the oleic acid coating process having been achieved successfully. In the case of the fluids produced by Liquids Research Limited measurements using photo correlation spectroscopy indicated that the dispersion was of a good quality. For simplicity these data are not shown.

From table 1 the properties of the ferrofluids used follow the expected trend for the amount of magnetite included in the oil. Clearly as a greater proportion of magnetite is added the density of the fluid rises in a manner to be expected. However note that samples 2 and 3 had a very similar concentration of magnetite but with difference in the saturation magnetisation ($M_S$) but sample 3 was deliberately engineered so as to have a higher viscosity. The higher viscosity would be expected to have a significant impact on the Brownian relaxation rate given by equation (2).

With an electromagnet with a 70 mm long Fe core (purity: 99.8%), a prototype device was built. This prototype was made of a plastic tube glued onto a glass slide with an area of 18 $\times$ 18 $mm^2$. The glass has a relative permeability of 1 and thus has no effect on the magnetisation induced in the ferrofluid. This was confirmed in the simulation. A Lakeshore 425 gaussmeter was used to measure the magnetic field generated by the electromagnets as a function of current as shown in figure 4. Images were taken to characterise the height and diameter of the dot as shown in figure 5.

## 4. Results and discussion

As listed in table 2 for ferrofluid 1 with the same electromagnet as used in figure 4, a clear increase in height and subsequent decrease in dot diameter is observed with increasing field magnitude. At a magnetic field of 24.3 kA $m^{-1}$, the measured height, 0.51 $\pm$ 0.05 mm, is within the UK Association for Accessible Formats (UKAAF) regulations for a braille dot which requires a diameter of 1.5 $\pm$ 0.25 mm and a height of 0.50 $\pm$ 0.10 mm. However, the diameter was measured to be 3.8 $\pm$ 0.4 mm which is more than twice of the allowed size. At lower fields the dot height decreases below the limit whilst the diameter increases slightly. In principle the diameter of the liquid dot can be controlled by varying the diameter of the coil and in particular the Fe core. However in this work we wish to demonstrate a proof of principle.

By replacing ferrofluid 1 with ferrofluid 2, a similar trend is obtained. The dot height increases with increasing field as more MNPs are attracted by the field, while the dot diameter stays the same within error. The dot height is larger than the UKAAF regulation, even at the lowest field applied, 0.61 $\pm$ 0.06 mm. The dot diameter is again more than twice the UKAAF specification. This result is to be expected given that fluid 2 has a much higher saturation magnetisation of 2.1 $\times$ $10^{-2}$ A $m^{-1}$ (21 G). However this leads to a significantly higher viscosity which will also reduce the response time.

Interestingly with ferrofluid 3, similarly to 2, the dot diameter varies minimally with increasing field. The dot height is found to double from 0.47 $\pm$ 0.05 mm to 1.0 $\pm$ 0.1 mm when the field is increased from 9.4 kA $m^{-1}$ to 24.3 kA $m^{-1}$. Here, the diameter of 0.47 mm lies within the UKAAF regulation. On the other hand, the diameter is measured to be 3.59 $\pm$ 0.36 mm with almost no change with field. Due to the significantly higher density of this ferrofluid, it is expected that a greater field is required to hold it in braille shape against gravity. This is not the case however probably due to the high particle concentration but due to the increase in the viscosity stabilising the larger dot. Although further optimisation in MNP concentration and the diameter of the electromagnet is

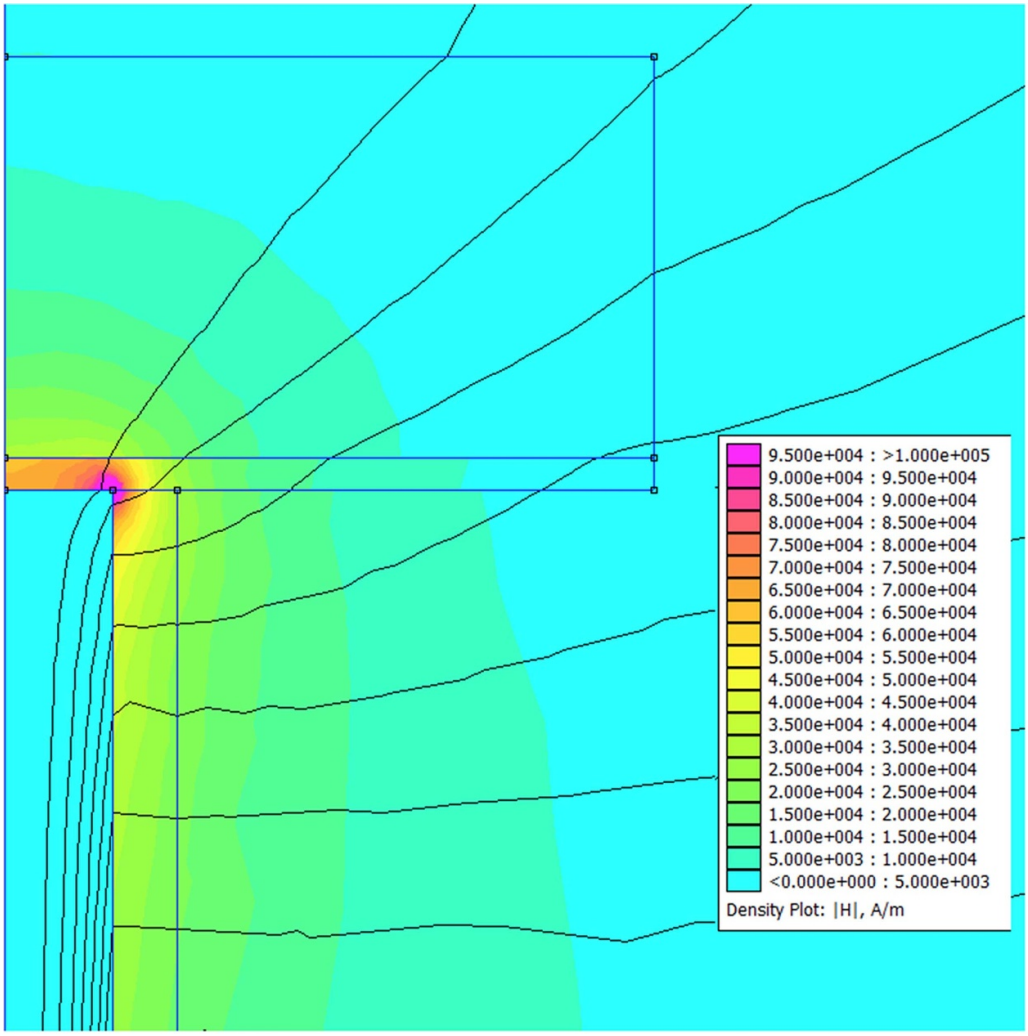


**Figure 3.** Iron-core electromagnet showing the simulated magnetic field strength density of the final design.

**Table 1.** Properties of the ferrofluids.

| Sample | Density (kg $m^{-3}$) (g $cm^{-3}$) | Viscosity (Pa· s) (cP) | $M_S$ (Wb $m^{-2}$) (Gauss) |
|---|---|---|---|
| 1 | 870 (0.87) | 0.00345 (3.45) | $1.1 \times 10^{-3}$ (11) |
| 2 | 1020 (1.02) | 0.00437 (4.37) | $2.1 \times 10^{-3}$ (21) |
| 3 | 1010 (1.01) | 0.00504 (5.04) | $1.0 \times 10^{-3}$ (10) |

required to meet the UKAAF requirements, the concept of the magnetic braille is successfully demonstrated.

Table 5 shows a comparison of the braille dot parameters for the three different fluids but under identical conditions of field. By way of example we have extracted data from tables 2, 3 and 4 for the case when the magnetic field applied was 20 kA $m^{-1}$. For ease of reference we also show the value of the saturation magnetisation for each of the fluids.

From the data in table 5 it is clear that the magnetisation and to some degree the viscosity of the fluid determines the dot height. For example increasing the value of $M_S$ by something just over a factor 2 results in almost a factor 2 increase in the dot height. Furthermore increasing the fluid volume also increases the dot height as can be seen from the disproportionate increase in the dot height when comparing the fluids with the viscosity of 3.45 cP to 5.04 cP. Of course in this case the fluid is subject to a field gradient so it appears that in the field gradient the greater rigidity of the fluid enables a higher dot to be produced. However the increase in viscosity may also have an effect on the re-write time for a given dot and hence further study is required to establish the exact relationship between the key parameters of saturation magnetisation of viscosity on the dot height.

It is also clear from table 5 that the dot diameter achieved is essentially identical for all three fluids. This indicates that the dot diameter is controlled exclusively by the dimensions of the coil and we believe in particular by the diameter of the steel core within each coil which had a diameter of 0.315 mm The independence of these two key parameters in generating suitable braille dots is of great importance because it means that

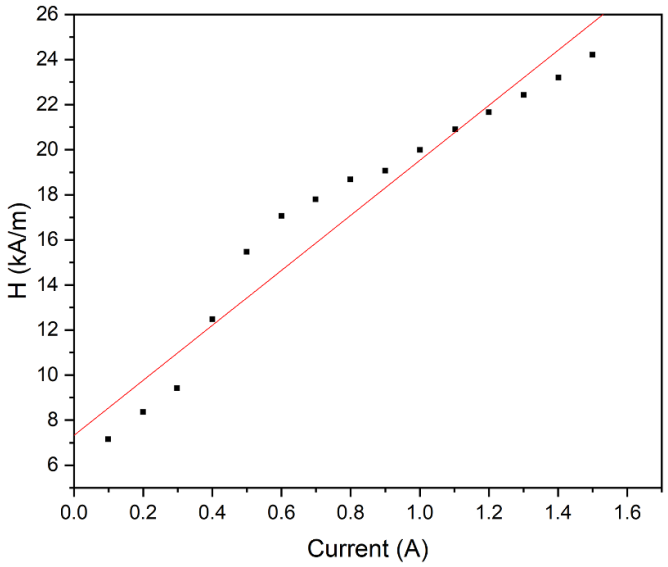


**Figure 4.** Measured field values from the electromagnet with 216 turns of 0.315 mm diameter wire and an Fe core of diameter 1 mm. A least square fit is shown as a red line. The offset without a current application is induced by the remanent magnetisation of the core used.

**Figure 5.** An image of a 'braille' dot.

**Table 2.** Dot measurements for ferrofluid 1 with the same electromagnet as used in figure 4.

| Current (A) | Magnetic field (kA m$^{-1}$) | Dot height (mm) | Dot diameter (mm) ±0.4 mm |
|---|---|---|---|
| 0.3 | 9.4 | 0.27 ± 0.03 | 4.4 |
| 0.6 | 17.1 | 0.34 ± 0.03 | 4.3 |
| 1.0 | 20.0 | 0.44 ± 0.04 | 4.1 |
| 1.5 | 24.3 | 0.51 ± 0.05 | 3.8 |

**Table 3.** Dot measurements for ferrofluid 2 with the same electromagnet as used in figure 4.

| Current (A) | Magnetic field (kA m$^{-1}$) | Dot height (mm) | Dot diameter (mm) ±0.4 mm |
|---|---|---|---|
| 0.3 | 9.4 | 0.61 ± 0.06 | 4.5 |
| 0.6 | 17.1 | 0.67 ± 0.07 | 3.9 |
| 1.0 | 20.0 | 0.71 ± 0.07 | 4.2 |
| 1.5 | 24.3 | 0.97 ± 0.10 | 4.3 |

**Table 4.** Dot measurements for ferrofluid 3 with another electromagnet from the one used in figure 4.

| Current (A) | Magnetic field (kA m$^{-1}$) | Dot height (mm) | Dot diameter (mm) ±0.4 mm |
|---|---|---|---|
| 0.3 | 9.4 | 0.47 ± 0.05 | 3.6 |
| 0.6 | 17.1 | 0.71 ± 0.07 | 3.7 |
| 1.0 | 20.0 | 0.93 ± 0.09 | 4.0 |
| 1.5 | 24.3 | 1.00 ± 0.1 | 3.8 |

the dot height and the dot diameter can be controlled without any interaction between the two parameters taking place. This should allow for a larger scale system to be designed and implemented relatively easily.

During the braille operation, the dots are found to be deformed by Joule heating induced by the electrical current flowing in the magnets. The time scale of deformation is measured to be on the order of 0.1 s, which is much longer than the dot deformation after removing the magnetic field (ms order). The heating effect can therefore be minimised by applying a pulsed current with the interval shorter than the deformation time after the field removal for heat dissipation. By optimising the amplitude and the period of the current pulse, the deformation of the dot due to heat can be eliminated. The limitation of the temperature is imperative for operation and another way in which this can be done is to use a magnetic core made from a material which has high magnetic permeability. This would decrease the current, and therefore the temperature, needed for the formation of the dot. Reducing the current within the coil results in a lower temperature and therefore a higher quality of dot.

For the purpose of proving the arrayed operation of ferrofluid braille dots can be achieved, four electromagnets with the same properties were installed to form an array of four magnetic braille dots. The separation of the dots is set to be 2.34 mm which is comparable with the UKAAF regulation. As shown in figure 6, individual operation of the dots is achieved without causing any cross-talk between them. The four dots shown in figure 6 are formed by four double-wound coils made from a material consisting of 99.9% pure iron. The saturation magnetisation of the ferrofluid used was 2.1 × 10$^{-2}$ A m$^{-1}$ (21 G).

For our magnetic braille we can estimate the dot stiffness using a calculation with the elastic modulus as proposed by Timoshenko *et al* [13].

$$E = \frac{2\left(1-v^2\right)aq}{w} \tag{3}$$

where $E$ is an elastic modulus, $v$ is a Poisson ratio, $a$ is the diameter of a probe, $q$ is stress per unit area and $w$ is the deformed height. For the dot formation with $w = 1$ mm and $v \sim 0.2$ to be detected by a human finger with $E \sim 20$ kPa [14], $q$ is estimated to be 1 kN, which can be within a detectable range. Additionally, the refresh rate can be on the order of ms as discussed previously. The formation of a dot can be detected by the touch of a finger. For a braille operation, the MNP solution needs to be shielded by a thin polymer film to avoid any contamination. Such magnetic braille can be placed on a track pad on a laptop

**Table 5.** Comparison of dot parameters at constant field.

| Sample | Magnetic field (kA $m^{-1}$) | Dot height (mm) | Dot diameter (mm) ±0.4 | $M_S$ (Gauss) | Viscosity (cP) |
|---|---|---|---|---|---|
| 1 | 20 | 0.44 ± 0.04 | 4.1 | 79 | 3.45 |
| 2 | 20 | 0.71 ± 0.07 | 4.2 | 188 | 4.37 |
| 3 | 20 | 0.93 ± 0.09 | 4.0 | 198 | 5.04 |

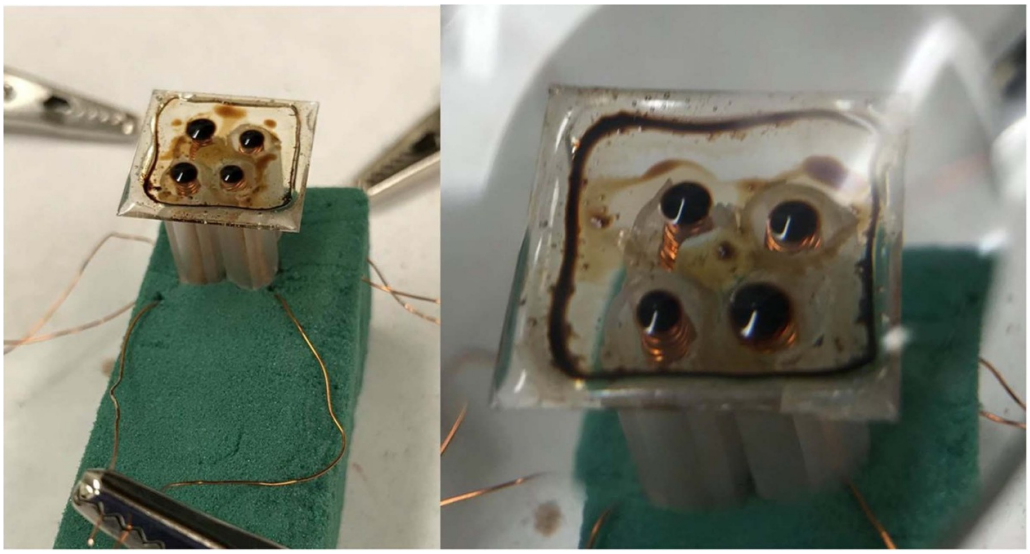

**Figure 6.** The final design with a ferrofluid present on the slide, showing the formed braille dots (left). A magnified image is shown on the right.

computer for example, offering an ideal braille for information technology.

## 5. Conclusion

Practical work has been carried out on the basis of the theoretical work to show effective formation of braille dots in a ferrofluid. It is found that a high viscosity and high MNP concentration is ideal by testing several ferrofluids. Dot height within the UKAAF regulations can easily be achieved with all used ferrofluids. The dots generated during this proof of principle study have a diameter (>4 mm) larger than the maximum allowed under the UKAAF guidelines. However this work has shown that whilst the dot height (0.4 ∼ 0.9 mm) is controlled by the key properties of the ferrofluid, i.e. the saturation magnetisation and the viscosity, the dot diameter appears to be controlled exclusively by the dimensions of the coils used and in particular the diameter of the Fe core inside the coil. This implies that the height and diameter of the dots formed are essentially independent of one another at least at sizes similar to those used in this work. Hence in addition to the proof of principle being demonstrated it also appears that the necessary design parameters are such that an ideal dot formation complying in both regards to the UKAAF specifications can be achieved.

## Data availability statement

All data that support the findings of this study are included within the article.

## Acknowledgments

This work is partially funded by EPSRC (EP/M02458X/1). Ferrofluid characterisation was carried out by Dr James Timmis of Liquids Research Ltd.

## ORCID iD

A Hirohata https://orcid.org/0000-0001-9107-2330

## References

[1] Benefits of braille (available at: www.royalblind.org/national-braille-week/about-braille/benefits-of-braille)
[2] NV Access (available at: www.nvaccess.org/)
[3] Becker J V, Hinton D E and Anderson H G Jr. 2004 Braille computer monitor *US Patent* 6,700,553
[4] RNIB (available at: https://shop.rnib.org.uk)
[5] Tamilarasan N, Thirumalini S, Nirmal K, Ganapathy K, Murali K and Srinath H 2016 Design and simulation of ferrofluid tactile screen for braille interface *2016 Int. Conf.*

*on Robotics and Automation for Humanitarian Applications (RAHA)* (https://doi.org/10.1109/RAHA.2016.7931890)
[6] O'Grady K, Popplewell J and Charles S W 1983 *J. Magn. Magn. Mater.* **39** 56
[7] Tari A, Chantrell R W, Popplewell J and Charles S W 1979 *Physica* B **97** 57
[8] Rosensweig R E 2002 *J. Magn. Magn. Mater.* **52** 370
[9] Finite Element Method Magnetics (available at: www.femm.info/wiki/HomePage)
[10] Exxon Mobil Corporation Performance fluids (available at: http://ww2.che.ufl.edu/unit-ops-lab/experiments/LLE/Isopar-M-properties.pdf)
[11] Exxon Mobil Corporation Isopar fluids for personal care products (available at: www.exxonmobilchemical.com/en/∼ /media/EB0D6F350FFD4BF782664F57343486E6.ashx)
[12] Liquids Research Limited (available at: www.liquidsre-search.com/)
[13] Timoshenko S P and Goodier J N 1970 *Theory of Elasticity* (New York: McGraw-Hill) pp 403–5
[14] Krouskop T A, Wheeler T M, Kaller F, Garra B S and Hall T 1998 Elastic moduli of breast and prostate tissues under compression *Ultrason. Imaging* **20** 260