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Development and Characterization of a Ferrofluid-based Tactile Learning Aid Display

Aaron Raymond See,[1*] Kohila Chandramohan,[1]
Aldrin Joshua Tolentino,[1,2] and Renann Baldovino[2]

[1]Department of Electrical Engineering, Southern Taiwan University of Science and Technology, Tainan 710, Taiwan
[2]Manufacturing Engineering and Management Department, De La Salle University, Manila 922, Philippines

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There are currently limited tactile learning aid materials for the blind and visually impaired, which incorporate refreshable displays with varying stiffness. In this research, we used a ferrofluid to develop a tactile learning aid display that creates bumps under the effect of a magnetic field to provide versatile stiffness and sufficient deformation for rendering 2.5-dimensional information. To improve the force feedback, the ferrofluid was further enhanced with iron particles and evaluated using a pressure sensor. Subsequently, a microcontroller was used to send commands via Bluetooth to remotely control the tactile display. A graphical user interface that allows users to enter words, perform simple calculations, and display simple shapes on the tactile display was developed. Results from the enhanced ferrofluid showed force feedback that is 45% stronger than that of a commercial ferrofluid. This study includes a comprehensive examination of the effect of magnetic field on enhanced ferrofluid and also shows that the formulation of an enhanced ferrofluid has raised the force feedback to 4.2 N and the maximum protrusion height to up to 3 mm. This innovative approach offers potential benefits for the development of advanced haptic devices for the education of the visually impaired. Lastly, the proposed tactile sensor module signifies a major leap in assistive technology, unlocking new opportunities for engagement, education, and improvement in the quality of life of the visually impaired population.

1. Introduction

The swift progression in assistive technology is paving the way for innovative solutions that cater to individuals with disabilities; however, a significant gap persists in servicing the visually impaired community and the medical sector. This gap is notably bridged by the burgeoning developments in haptic technology, enabling tactile interaction with virtual objects.(1,2) In this study, we present the development of a pioneering haptic display module using ferromagnetic materials. Ferrofluids, composed of substances such as iron oxide and carbonyl iron, exhibit

*Corresponding author: e-mail: aaronsee@stust.edu.tw
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remarkable potential in creating tactile sensations resembling those of various surface textures.[3] However, the amalgamation of these materials in haptic devices faces significant challenges, necessitating meticulous planning and execution throughout the development stages. The focal point of this initiative is to develop a tablet-like device that facilitates education and communication for disabled individuals while also investigating its possible use in teleoperations. Commercially available tactile displays have many features that make tactile graphics accessible to the blind and visually impaired, such as a Dot Pad, which is a tactile display using electromagnetic actuators that can be refreshed and shows texts and visuals.[4] Haptic displays utilizing rheological fluids surpass pin-based haptic displays as they can generate tactile bumps with wide ranges of heights and stiffness levels, essential for replicating various biological textures without complex designs.[5,6] As part of the current research, ferrofluids are being used to create dynamic, refreshable, and shape-changing tactile displays aimed at those with vision impairments.[7–10] Touch sensors such as the array of force-sensitive resistors are used to sense the interactive points rendered by a haptic display.[11–13] Our prototype will be evaluated using a pressure sensor to create an assistive device that will allow users to perceive structural nuances and to enhance the capabilities of haptic technology significantly. In essence, this study stands as a critical milestone in the field of assistive technology, heralding a more inclusive and adaptive future. Through this research, we not only promise to aid the visually impaired but also aspire to revolutionize educational paradigms, potentially elevating the quality of life of various communities.

This paper is organized as follows. In Sect. 2, we offer an overview of the operating principle of the ferrofluid. In Sect. 3, we introduce a new formulation of the enhanced ferrofluid and outline the experimental setup and procedures implemented to assess the prepared fluid's performance and provide a detailed description of the development of the haptic module. In Sect. 4, we describe in detail the results of the experiments and provide a discussion of the findings. The paper concludes with Sect. 5, which is a summary of the research, highlighting the key contributions of our work and offering insights into potential future work.

2. Working Principles of the Ferrofluid

The proposed tactile learning aid display relies fundamentally on controllable smart fluids that form the basis for translating the haptic stiffness layer. One such controllable fluid is ferrofluid, which can adjust its rheological properties in response to an applied magnetic field. More precisely, this fluid can transform its physical state, shifting from liquid to solid by altering its viscosity.[14] This alteration in viscosity is induced by the magnetic flux generated by an external magnetic field. When exposed to this external magnetic effect, the fluid's increased viscosity causes a rise in yield stress, allowing it to transition from a liquid to a solid-like state within microseconds.[15] The core feature of controllable fluid technology lies in this reversible change in viscosity. At room temperature, the nanoparticles within the ferrofluid exhibit superparamagnetic properties.[16] When a magnetic field is present, or in the "ON state," metal particles within the fluid are guided to form a chain-like structure. The yield stress of the fluid can be controlled, either augmented or diminished, depending on the magnetic field's strength, as expressed in the following equations:

$$\tau = \tau(B) + \eta \cdot \gamma, \quad (1)$$

$$B = f(H), \quad (2)$$

where magnetization is expressed as the flux density B (Tesla) as it varies with the magnetic field strength H (A/m), η is the dynamic viscosity (Pa s), τ is the shear stress (N/mm^2), and γ is the shear rate (1/s) of the fluid. η is proportional to τ as

$$\eta = \tau / \gamma. \quad (3)$$

Then, the kinetic viscosity (m^2/s) of the fluid is defined as

$$\vartheta = \eta / \rho, \quad (4)$$

where ρ denotes the density measured in kg/m^3. Each metallic particle within a magnetic field transforms a dipole, consisting of both north and south poles.

This process allows for the potential formation of chains among proximate particles, leading to a mechanical blockage of fluid flow, thereby increasing its viscosity. The organization of these particle chains is governed by the arrangement of magnetic flux lines in the magnetic field. By manipulating the magnetic field strength, the mechanical resistance to the flow of this chain structure can be modified, facilitating transitions in viscosity from a liquid state to a solid state.[17] Once the magnetic field is deactivated, the liquid reverts to its original state.

On the other hand, a ferrofluid requires an extremely strong magnetic effect for its transition from the liquid state.[18] The pronounced yield stress behavior in a ferrofluid is almost negligible, whereas the capacity to form a chain structure, leading to mechanical resistance to flow, is integral to carbonyl-iron-based fluids.

3. Methodology

The designed system is composed of two primary stages: the crafting of an enhanced ferrofluid utilizing an existing ferrofluid and the assembly of a haptic module. The synthesis of an enhanced ferrofluid and its assessment through sensing techniques are demonstrated. A pressure sensor is the primary sensor used to sense the force feedback of the tactile display system. This haptic module can present structural details, and the force feedback stemming from tactile fluid bulges prompts the modification of different forms and structures.

3.1 Synthesis of enhanced ferrofluid

Carbonyl iron (CI) is one of the most commonly used particles to prepare magnetorheological fluids owing to its high magnetic permeability, soft magnetic properties, and common availability. Thus, an enhanced ferrofluid is prepared by mixing Ferrotec's EFH1 series of ferrofluid with CI particles (from Sigma Aldrich) with a grain size of 5–9 µm and a density of 7.86 g/mL. Our new approach is to improve the efficiency of the ferrofluid by involving a CI mixture to achieve a wide range of stiffness levels and various heights of bumps to facilitate a multidimensional haptic display. In terms of viscosity, it is possible to delineate the difference in viscosity more accurately, which is 6 cP for ferrofluid and 280 cP for magnetorheological fluid (MRF). For instance, while ferrofluids typically exhibit yield stresses of around 10 kPa, MRF may attain yield stresses of up to 100 kPa.(19) Owing to the particle size, ferrofluid exhibits remarkable stability, and their particles are less abrasive than those of MRF.

When using larger and more numerous ferromagnetic particles, more torque is generated in the ON state, but this also increases the fluid's viscosity when in the OFF state. Sedimentation is a prominent issue because of the substantial density disparity between the magnetic particles and the base fluid. Additives such as stabilizers (surfactants) are critical in enhancing settling stability, which is essential for counteracting van der Waal's attractive forces between particles. Therefore, the quantity of magnetic particles considerably affects the fluid's responsiveness and performance relative to the magnetic field. The methodology is aimed at refining the ferrofluid's viscosity and yield stress by incorporating micrometer-sized CI particles. These substantial disparities in yield stress are attributed to the larger size (microns) of CI particles, which are known for their higher magnetization in addition to the nanometer size of the magnetite particles that exist in ferrofluids. As sedimentation is typically greater in MRF than in a ferrofluid, this technique is favored to enhance yield stress and prevent clumping over time, rather than directly using MRF.

EFH series ferrofluids are stable colloidal suspensions of magnetic nanoparticles in a liquid carrier, with the particles being coated with a stabilizing oil-soluble dispersing agent (surfactant) to inhibit particle clustering when the ferrofluid is exposed to a magnetic field gradient. These dispersants, ranging from 6 to 30% by volume, inhibit the agglomeration of the nanometer-sized particles (3–15% by volume) within the ferrofluid.(20) Since no extra surfactants are added to control the additional micrometer-sized CI particles, the CI mixture is introduced only up to 30% by volume and properly mixed using a stirrer that gradually reaches a speed of 700 rpm to create the enhanced ferrofluid. The introduced micrometer-sized CI particles contribute to compact packaging with the surfactant-coated nanoparticles in the ferrofluid when an external field is applied.

3.2 Experimental setup for assessment of enhanced ferrofluid

Magnetite particles (Fe_3O_4), having an average diameter of around 10 nm, are significantly smaller than the micrometer-sized iron particles used, making the simultaneous observation of both by transmission or scanning electron microscopy technically challenging. Therefore, an experiment was carried out to juxtapose the tactile feedback magnitudes of both pure and enhanced ferrofluids. These were placed in uniformly sized pouches (3.5 cm^2) constructed of thermoplastic polyurethane (TPU), each filled with an equal volume (2.5 ml) and exposed to a magnetic field strength of 125 µT/m generated by an electromagnet capable of a holding force of 3.5 kgf. A Keyes pressure sensor, which is a common force-sensitive resistor, was employed to gauge the force feedback from the TPU pouches. The external power source was connected to the electromagnet, which was positioned on a flat support block. As the clamp desk was constructed from a ferromagnetic material, a cylindrical plastic spool and two nonferrous coins were used to create a separation between the desk and the ferrofluid pouch, to prevent any magnetic interference.

This arrangement is depicted in Fig. 1. The control of the electromagnet was facilitated through Arduino, and it was programmed to toggle ON and OFF at intervals of 1000 ms. This enabled the monitoring and measurement of alterations in force as the electromagnet cycled between the OFF and ON states. The assessment and comparison between the newly developed smart fluid and the conventional ferrofluid were carried out, with the findings presented in Sect.4.

3.3 Hardware setup design

The tactile learning aid display module mainly consists of electromagnets, an enhanced ferrofluid, a supporting base board, and the controlling electronic system. The module is designed with the proposed setup of 20-mm-diameter DX2040L electromagnets with a holding force of 3.5 kgf arranged in a 3 × 5 matrix array to have a display size of 6 × 10 cm^2. The electromagnets were placed in consideration of a 20 mm center-to-center distance to minimize the interference of the magnetic field and to maximize the magnetic field strength at the surface. TPU with a thickness of 0.15 mm is chosen to encapsulate the fluid since it is thin and strong enough to withstand the pressure and is a leakage-free material. Then, the encapsulated pouch was carefully sealed using a heat sealant. EFH1 is the primary material for the construction of the haptic array module; a schematic view of a cell with a single electromagnet of the module is shown in Fig. 2.

The control system for the module was built with an ESP-32 development board, which serves as the system's primary component to control and actuate the electromagnets. Data are

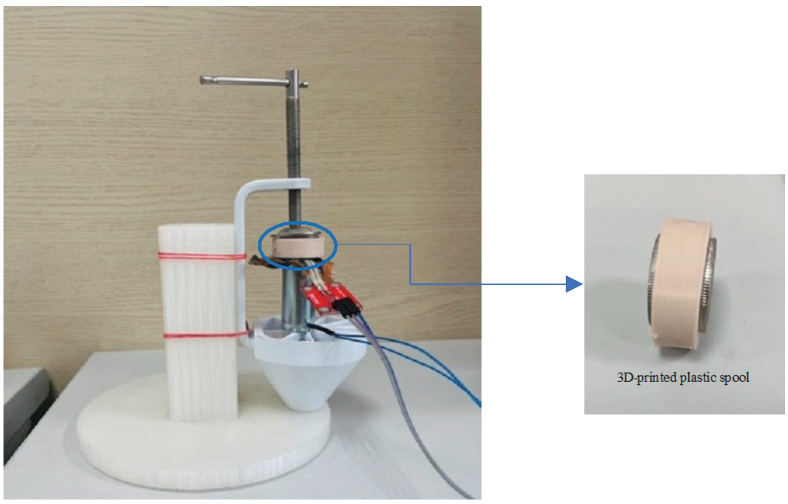

Fig. 1. (Color online) Experiment setup for measuring the force feedback.

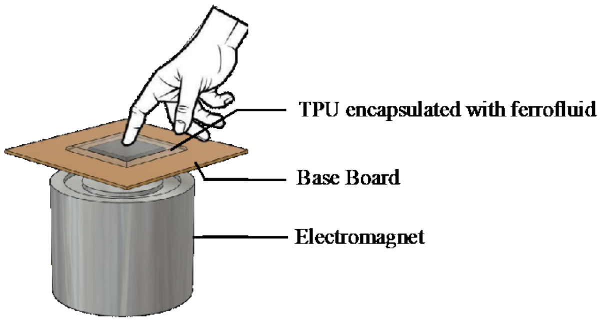

Fig. 2. (Color online) Schematic view of a single cell.

transferred via Bluetooth from a laptop computer. The serial data and serial clock lines of the ESP-32 produce specific electrical signals during this communication process. The MikroE 1898 PWM Click Board served as an I2C protocol and was particularly advantageous owing to its ability to support multiple slave devices with a simple two-wire connection, making it ideal for applications requiring efficient communication with the 15 electromagnets used to actuate the ferrofluid. The current flowing through each electromagnet can be varied by changing the duty cycle of the PWM signal produced by the Click Board. Subsequently, the ULN2803 IC was adopted to adequately operate the electromagnets. Each electromagnet draws a high current of 250 mA, which results in a power rating of 6 W per electromagnet, and the whole circuit consumes at least 90 W of power cumulatively. Nonetheless, it is only permitted to consume 500 mA, which is sufficient for the investigation. The proposed system architecture is shown in Fig. 3. A Python-based user interface for Windows OS and a wireless Arduino-based robotic process control the algorithm for electromagnet activation.

4. Results and Discussion

We provide a detailed evaluation of each of the two segments in this section: (1) the comparison and evaluation of the prepared enhanced ferrofluid and (2) the evaluation of the tactile learning aid display.

4.1 Comparison and evaluation of enhanced ferrofluid

The packaged ferrofluids demonstrate an inherent force, amounting to 29.7 N, originating from the essential tightness needed to secure the pressure sensor between the spool and the pouch. Two pouch variants, each containing distinct fluid types, were tested individually under an electromagnetic field with a magnitude of 132.01 gauss, produced by the electromagnet DX2040. The pouch with the commercial ferrofluid exhibited force feedback registering at 32.6 N, while its counterpart containing the enhanced ferrofluid reached a peak force feedback of 33.9 N. After accounting for the force introduced by the apparatus itself, the force feedback values of both the ferrofluid and enhanced ferrofluid pouches are obtained and graphically represented in Fig. 4.

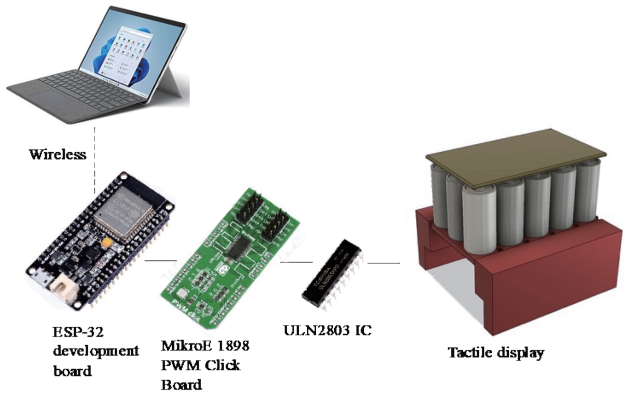

Fig. 3. (Color online) System architecture of wireless tactile display.

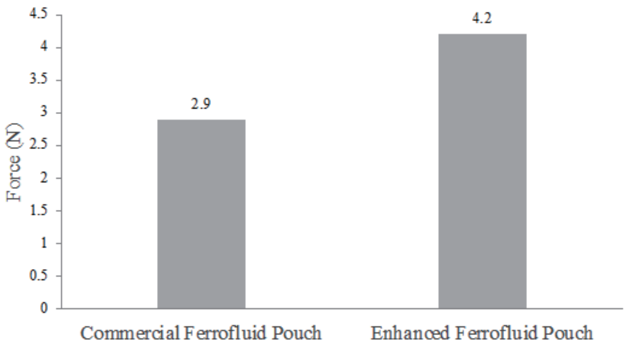

Fig. 4. Force feedback values of commercial and enhanced ferrofluid pouches.

To further substantiate the superior efficacy of the formulated EFH1, the protuberance height induced by the permanent magnet was measured. Both pouch variants were exposed to an intense magnetic field, marked at 300 gauss, sourced from a permanent magnet. Precise measurements of the protrusion height were conducted using a digital micrometer, and it was found that the enhanced ferrofluid height was larger by 1 mm.

The pouch with the enhanced ferrofluid, including the carbonyl iron particles, demonstrated a maximal protrusion height with a difference of 1 mm compared with the pouch incorporating the commercial ferrofluid. Therefore, the enhanced ferrofluid's ability to create a protrusion in a strong magnetic field showcases its potential for versatile stiffness and a wide range of morphological changes crucial for advanced haptic displays compared with the existing systems. Thus, we proceeded with EFH1 for the tactile module construction, and its further evaluations were carried out with various parameters as described below.

4.2 Evaluation of tactile pouch and electromagnet

In the experimental configuration, the enhanced ferrofluid pouch positioned over the DX2040 electromagnets facilitated the tangible deformation, clearly showing the target's morphology, rigidity, and intricacies. Deformation is predominantly modulated by the magnetic flux density originating from the electromagnet, which is in turn affected by its operational DC voltage (24 V) and input current. As depicted in the accompanying graph, there exists a direct correlation between the supply current and voltage to the electromagnets, which correspondingly enhances the magnetic flux density. As per the data, the DX2040 electromagnets can generate a peak magnetic flux density of 132 gauss at its operational boundary defined by input voltage, contingent upon the varying input current, as shown in Fig. 5.

The tactile elevation, instrumental in emulating the surface contours of the target object, is also modulated by the electrical input parameters. An exploration into the relationship between the tactile elevation and electrical inputs was conducted at a constant voltage of 24 V DC, while progressively augmenting the current to its upper limit of 0.25 A. The results are shown in Fig. 6.

In a subsequent assessment, the force feedback exhibited by the smart fluid-filled pouch was quantified. This analysis reaffirms the direct proportionality witnessed in preceding evaluations. At the electromagnet's maximal operational strength (24 V DC, 0.25 A), the force feedback peaks at 4.2 N, as shown in Fig. 7.

Consequently, the synthesized fluid is demonstrated to be adept at conveying precise tactile information; this is an impressive result compared with the existing systems,[7] and it is greater than the existing system's force feedback achieved with a permanent magnet.[21]

Figure 8 shows the graphical user interface wherein users can input characters including some punctuation marks in the word display segment and perform a simple mathematical calculation by entering two numbers and an arithmetic operator in the calculator segment. The graphical user interface also allows users to display simple shapes by selecting predefined

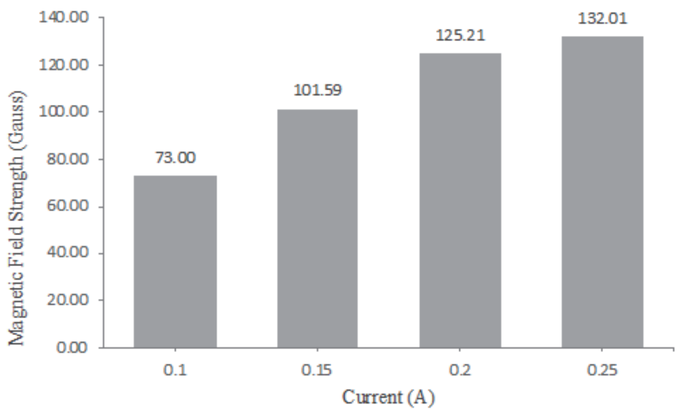

Fig. 5. Magnetic field strength vs current.

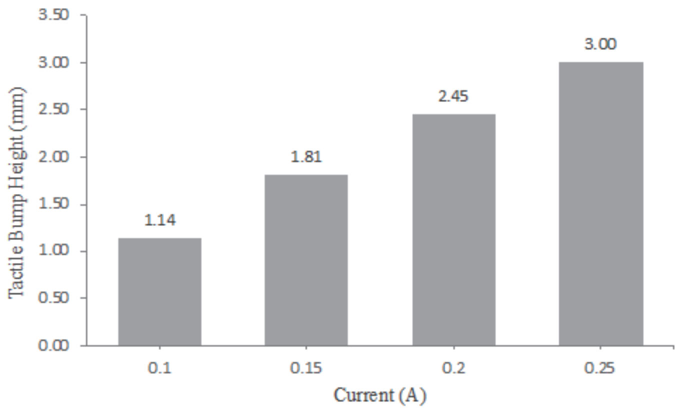

Fig. 6. Tactile bump height vs current.

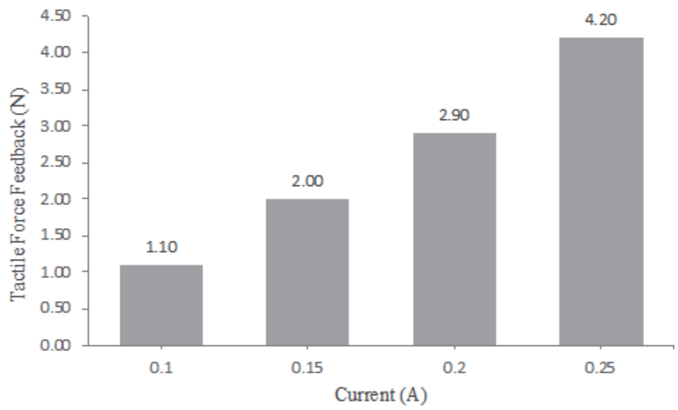

Fig. 7. Force feedback vs current.

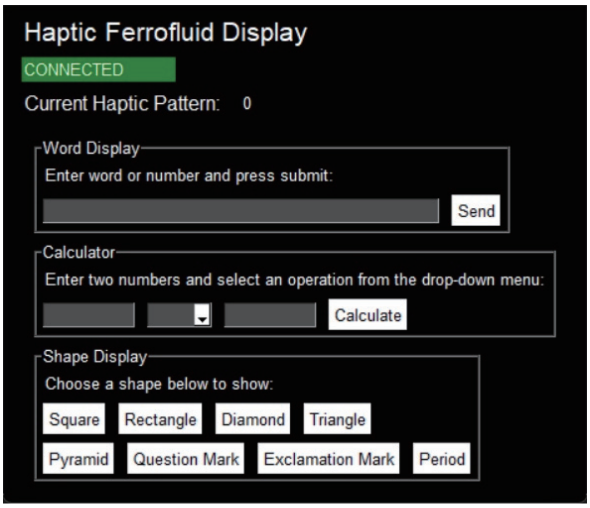

Fig. 8. (Color online) A graphical user interface is utilized to send commands to the tactile learning aid display.

options. Figure 9 shows the numbers “1” and “3” formed with ferrofluid directly and within an enclosed TPU pouch. The tactile display system is capable of displaying the 26 characters of the English alphabet; the patterns of letters A, B, and C are presented in Fig. 10.

Similarly, the tactile display system can display seven shapes. Some of the patterns of the shapes mentioned in the graphical user interface are presented in Fig. 11. The dimensions of all the patterns formed by the tactile display system rely on the dimensions of the electromagnet’s matrix, which is $6 \times 10\ cm^2$. For some patterns such as squares and triangles, the entire rows or columns of the matrix might not be utilized completely. In such cases, the dimensions of such patterns would differ.

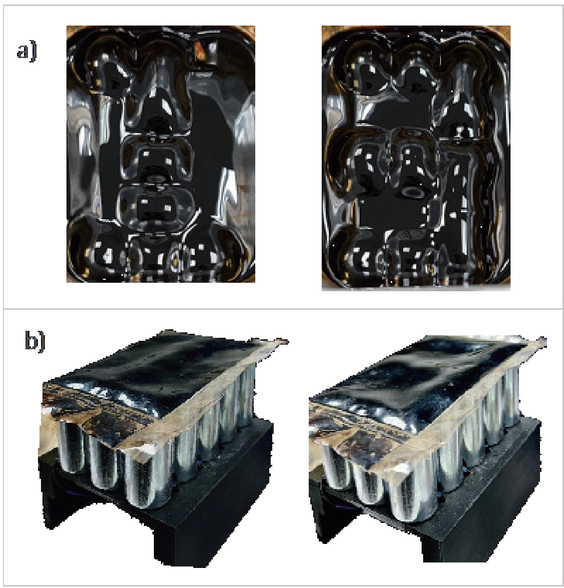

Fig. 9. (Color online) Display of numbers “1” and “3” formed with tactile bulges. (a) Without TPU pouch (top view). (b) With fluid-encapsulated TPU pouch (side view).

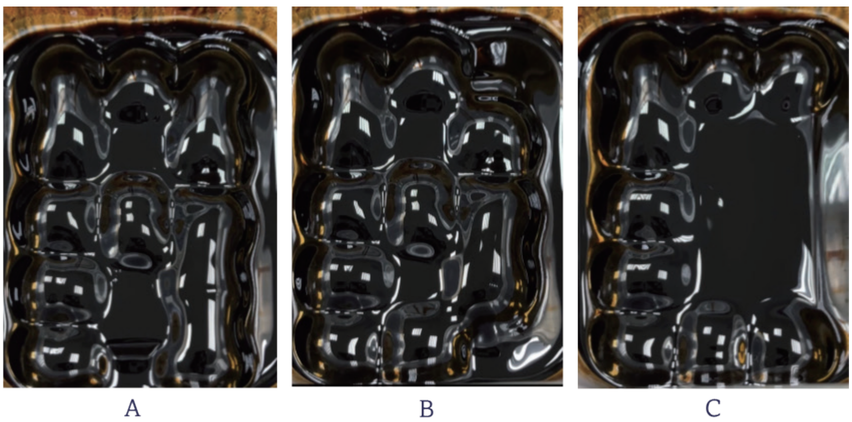

Fig. 10. (Color online) Display of letters “A”, “B” and “C” formed with tactile bulges.

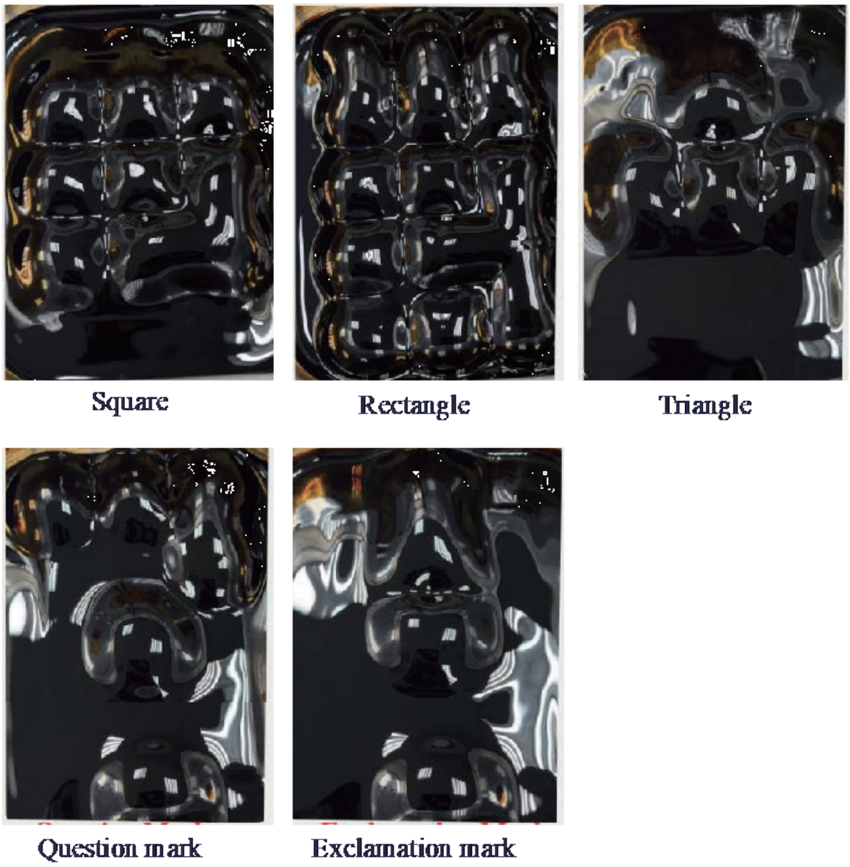

Fig. 11. (Color online) Display of shapes formed with tactile bulges.

5. Conclusions and Future Works

In this research, we proposed a new approach to developing a tactile learning aid display based on a formulated enhanced ferrofluid. Our methodology manifested the capability to induce force feedback, leveraging the attributes of the enhanced ferrofluid and assessed through a tactile pressure sensor. Through the incorporation of the enhanced ferrofluid, our system can induce multidirectional forces vertically through tactile protrusions and horizontally through tactile stimuli experienced during lateral finger movement. The entire assessment carried out by varying each parameter has been described to demonstrate the feasibility of the device. Furthermore, the results of experiments also verified that the proposed tactile device can display detailed shapes with tactile bumps, and the comprehensive quantitative assessment results underscored that these tactile representations function cohesively without any disruptions. In future research, we aim to enhance the resolution by employing multiple arrays of fluid-filled pouches that can be individually activated using highly compact and potent electromagnets.

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About the Authors

Aaron Raymond See was born in Manila, Philippines, and received his B.S. degree in Electronics and Communications Engineering from De La Salle University, Manila, in 2006. He obtained his M.S. and Ph.D. degrees in electrical engineering with a major in biomedical engineering from Southern Taiwan University of Science in Technology in 2010 and 2014, respectively. Subsequently, he did his postdoctoral research in neuroscience at the Brain Research Center, National Tsing Hua University, Hsin Chu, Taiwan. He is currently an associate professor in the Department of Electrical Engineering at Southern Taiwan University of Science and Technology. His research interests are in assistive device design and development, haptics, machine learning, and biomedical signal processing. (aaronsee@stust.edu.tw)

Kohila Chandramohan hails from Tamilnadu, India. She received her B.S. degree in electronics and communication engineering from K.S. Rangasamy College of Technology, India in 2017. She is currently pursuing her M.S. degree in electrical engineering and is a researcher at the Haptics Enhanced Assistive Devices Lab at Southern Taiwan University of Science and Technology, Taiwan. Her current research interests include tactile sensors, piezoelectrics, and haptics. (mb02b206@stust.edu.tw)

Aldrin Joshua Tolentino hails from Laguna, Philippines. He earned his B.S. and M.S. degrees in manufacturing engineering and management from De La Salle University, Manila. His research focuses on assistive technologies, haptic devices, and biomedical informatics. He was a research assistant at the Institute of Biomedical Engineering in Manila in 2019 and a researcher in the Haptics Enhanced Assistive Devices Lab at Southern Taiwan University of Science and Technology, Tainan, Taiwan, from 2022 to 2023. (aldrin_tolentino@dlsu.edu.ph)

Renann G. Baldovino is an associate professor in the Department of Manufacturing Engineering and Management at De La Salle University, Manila, Philippines. He handles courses in electronics design, biomedical instrumentation, and artificial intelligence (AI). Prior to the academe, he had already developed a strong foundation in the research field of mechatronics design. Currently, he writes papers on applications of advanced controls and computational intelligence to manufacturing systems and industrial processes. He also serves as a technical consultant at the Department of Science and Technology of the Philippines. (renann.baldovino@dlsu.edu.ph)