4x4 of Solenoid-based Tactile Matrix Display with Miniaturization Adapter

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Abstract: This study presents two portable 4x4 solenoid-based tactile matrix display prototypes that use commercial of-the shelf (COTS) miniature DC solenoid actuators. Both prototypes are made from 16 pieces of an Open Frame Actuator Linear Mini Push Pull Solenoid Electromagnet. Prototype 1 is a 4x4 Braille-like tactile matrix display with a faceplate of 50 mm side-length and 12 mm pin pitch. It is used to study human's ability to recognize Braille-like patterns by hand exploration of the tactile surface. On the other hand, the Prototype 2 is a miniaturized tactile display of prototype 1 using a tactile matrix display miniaturization adapter that reduced the matrix pin surface area by around 8 times forming a 4x4 fingertip tactile matrix display. It is made up of flexible plastic tube fitted with a flexible wire connected to the plungers or pins of the tactile actuators. Moreover, it can also be combined with a tactile display simulator that scans a binary image to feel the surface area or edges of an image using Canny edge detector. The prototypes developed in this study might be used in the fields of telerobotics, Virtual Reality (VR), and Human-Computer Interaction (HCI).

Key Words: tactile matrix display; miniaturization adapter; edge detection

1. INTRODUCTION

The interdisciplinary research on haptics covers perception (Lederman & Klatzky, 2009), psychophysics (Ide et al., 2019), vision substitution systems for the blind and visually impaired that dates back to their development in the 1960's (Bliss et al., 1970; Collins, 1970), virtual reality (VR), mechanism design and control, bio-medical engineering, mobile communication (Kwon et al., 2010), telerobotics (Kappassov et al., 2015; Shen et al., 2000), material recognition (Xie et al., 2019), and Human-Computer Interaction (HCI) (Visell, 2009).

A tactile display is a human-computer interface that can reproduce tactile parameters of an object, such as shape, surface texture, and temperature (Chouvardas et al., 2005). Tactile displays can be interfaced with other electronic devices such as computers (Bliss et al., 1970), communication media, mobile phones (Kwon et al., 2010), and car appliances. It has also been used in e-commerce, telepresence (Kappassov et al., 2015; Shen et al., 2000), and Virtual Reality (VR) applications

(Rotard et al., 2008). They are built with a number of pins (taxels or tactile pixels) (Benali-Khoudja et al., 2007), which can be lifted or lowered forming a matrix of pins arranged by lines and columns. Tactile displays come in different sizes and pin numbers (3x3 to 64x73) (Dot pad, 2018), with different types of tactile actuators such as: solenoids (Salsedo et al., 2011), vibration motors (Collins, 1970), voice coil motors (Szabo & Enikov, 2012), piezoelectric (bimorph and small ultrasonic linear motor) (Bliss et al., 1970; Kyung & Lee, 2009), Smart Memory Alloy (SMA) (Sawada, 2016), Shape Memory Polymer (SMP) (Besse et al., 2018), pneumatic (Russomanno et al., 2017), and stepper motor (Shimizu, 1986). Compared to Braille, tactile display pins are not grouped. All pins have the same displacements to the neighboring pins so that no gaps will emerge when displaying graphics (Benali-Khoudja et al., 2007). Aside from matrix of pins that can go up and down, tactile display can also be made of pins or nodes that vibrates at different frequencies (Ikei, 1997).

Most tactile displays are expensive, factory-made, and have complicated parts. This paper presents two portable tactile display prototypes that can be constructed using commercially available miniature solenoid actuators UEETEK 6V DC Open Frame Actuator Linear Mini Push Pull Solenoid Electromagnet as shown in Fig. 1. Prototype 1 is a 4x4 Braille-like tactile display that can be used to study human's ability to recognize Braille-like patterns using hand exploration. Prototype 2 is based on prototype 1 with a miniature fingertip 4x4 tactile matrix display made by using a miniaturization adapter that reduced the tactile surface area of prototype 1 by 8 times. This fingertip tactile display is combined with a tactile matrix display simulator

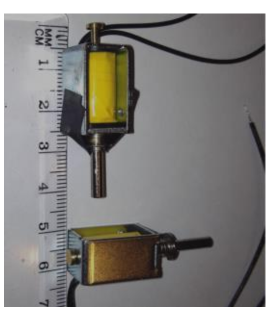

Fig. 1. Commercially available miniature DC solenoids.

that scans a binary image or edges of an image using Canny edge detector.

Details of the hardware of the two prototypes are discussed in Section II, discussion of software in Section III, experimental results in Section IV, followed by conclusion and recommendation in Section V.

2. CONSTRUCTION OF THE PROTOTYPES

The two prototypes in this study used DC solenoids as shown in Fig. 1. Both have the same basic circuitry guided by the schematic diagram shown in Fig. 2. They operate using 5V DC supply, with IRL540 MOSFET driver to drive each solenoid, and an Arduino microcontroller to control the actuation of each tactile actuator.

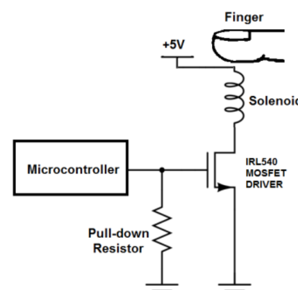

Fig. 2. Solenoid Tactile Schematic.

2.1 Prototype 1: The 4x4 Tactile Display

Prototype 1, as shown in Fig. 3, is made by grouping 16 solenoids presented in Fig. 1. Each solenoid has the followings specifications (DC Solenoid, 2022): Force and Stroke: 40g/2mm; Energized Rate: 25%; Body Size: 20 x 12 x 11mm (L*W*T); Plunger Bar Size: 3 x 40mm (D*L). The displacement from center of one plunger to another in a 4x4 matrix is 12 mm. Each solenoid consumes around 625 mA of current at 5V DC supply voltage.

In order to insulate the user from the heat dissipated by the solenoid during continuous operation, wooden dowel pins with 4 mm diameter and 10 mm in height were put on top of each plunger as shown in Fig. 3b. White acrylic plastic plate with holes acts as the surface of the 4x4 tactile matrix which supports the hand of the user during pattern exploration. The surface area is 25 cm^2.

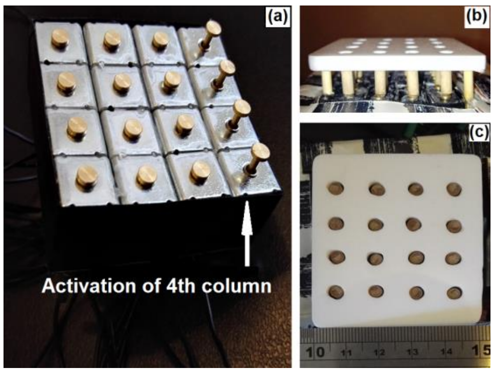

Fig. 3. Prototype 1: 4x4 Tactile Display. (a) 4th column activated, (b) wooden pins are put on top of each plunger to insulate the user from the heat dissipated by the solenoids during prolong usage, and (c) top view.

2.2 Prototype 2: 4x4 Fingertip Tactile Display

Using a novel miniaturization adapter, we reduced the surface area of prototype 1 from 2,500 mm^2 to 289 mm^2 in in Fig. 4a and Fig. 4b respectively. Moreover, the pin pitch of 12mm of prototype 1 was reduced to pin pitch of 3.5mm in prototype 2.

To the best of our knowledge, this is the first to report a miniaturization adapter to reduce the surface area of a tactile display that uses COTS solenoid. The adapter is made up of flexible plastic tube fitted with a flexible wire connected to the plungers. Maximum deflection of wires can found at the corner pins which is 20° in this is study. Moreover, this tactile display miniaturization adapter can also be fitted on horizontally mounted actuators as shown in Fig. 4d. The tactile pins can be controlled individually. Each pin can be activated in an up or down static position or can be activated in tapping mode wherein frequency, duty cycle, and time duration of the vibrating pins can be varied.

3. SOFTWARE

The firmware that controls the actuation of each solenoid in both prototypes runs using Arduino IDE. We can control every pin to move 'up', 'down', or

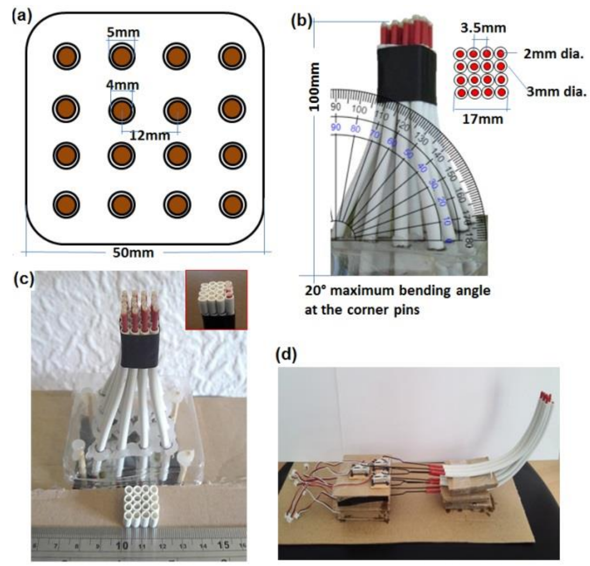

Fig. 4. Prototype 2: 4x4 Tactile display with miniaturization adapter: a) prototype 1 display dimensions, b) prototype 2 display dimensions, c) prototype 2 with 4th column activated in the inset picture, and d) horizontal to vertical actuator display conversion.

vibrate at different frequencies. We developed two Graphical User Interfaces (GUI). The first GUI was programmed using Processing software that displays different tactile patterns that can be clicked and the corresponding pattern will be actuated on the tactile display. The second GUI is a 4x4 tactile matrix simulator using Python. The tactile simulator is a square GUI forming a Region of Interest (ROI) with 16 small circular sections representing the 16 tactile pins. The ROI can move across an image on the computer display using computer mouse. The flowchart for the scanning ROI algorithm is shown in Fig. 5. Each small section in the ROI evaluates the average black or white pixel color within its boundary. The simulator can be used to scan a binary image of a regular polygon or edges of an image using Canny edge detector. If the small section is more than 50% black, this small section of the ROI is filled with color yellow and an 'up' signal is sent to the microcontroller to activate the corresponding tactile actuator pin. Moreover, if the small section is less

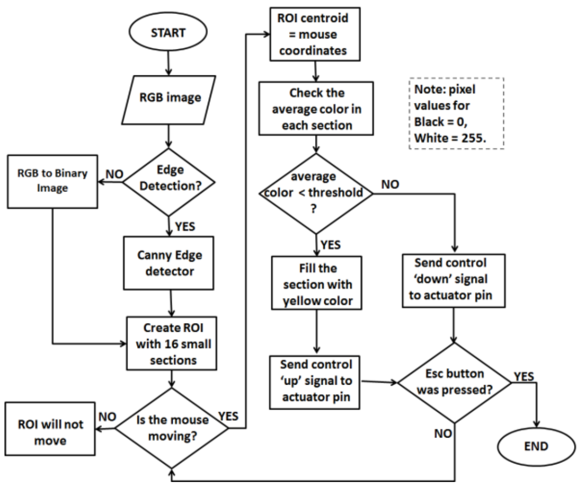

Fig. 5. Tactile display simulator flowchart.

than 50% black, this small section of the ROI sends a 'down' signal to pull down the corresponding pin.

4. RESULTS & DISCUSSION

We are going to introduce two types of applications using our prototypes. Detailed discussions are as follows:

1) *Prototype 1: Braille-like pattern recognition:* We used prototype 1 to study Braille-like pattern recognition and the experimental setup is shown in Fig. 6. Here, pins are actuated for 5 seconds to display different tactile patterns such as

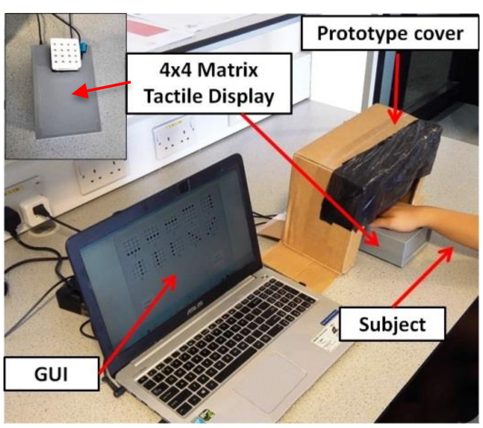

Fig. 6. Experiment setup for prototype 1.

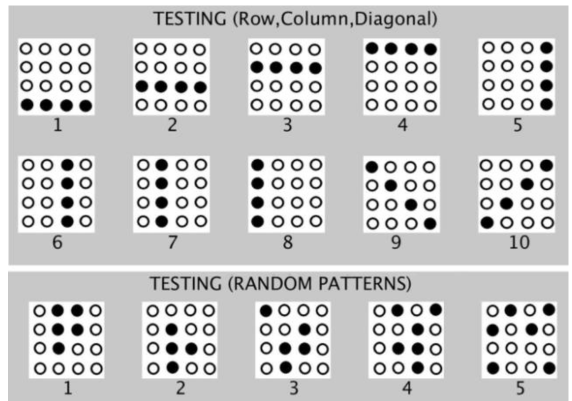

Fig. 7. Braille-like patterns.

row, column, diagonal, and random patterns as shown in Fig. 7. Patterns are played 5 times pseudo-randomly. The user is free to explore/feel the actuation using their dominant hand. Eight right-handed subjects (3 male, 5 female with ages 18-40 years old) participated to the experiment after giving informed consent. Subjects signed a written consent form approved by Liverpool Hope University, research ethics committee, School of Mathematics, Computer Science and Engineering (REC Reference number: S–24-06-2019 SEL 087). Our results, as shown in Fig. 8, show that they can recognize row, column, and diagonal activation with 93.25% mean accuracy. In total, top and bottom rows and leftmost and rightmost columns recognition average accuracy is 96.25%. Moreover, diagonal identification average accuracy is 98.75% and random pattern recognition is about 84.5%.

2) *Prototype 2: Edge detection:* Prototype 2 can be coupled with the 4x4 tactile matrix actuator simulator with a scanning ROI as shown in Fig. 9c. The actual 4x4 fingertip tactile prototype bottom-left corner of the figure. Six pins are in the 'up' position corresponding to the 6 yellow-filled circles of the 4x4 tactile matrix simulator. The simulator uses Canny edge detection algorithm that can trace the edges of an image within the ROI. The RGB picture of a hand in Fig. 9a was converted to gray scale followed by morphological transformation such as Gaussian blur before applying Canny edge detector. The Canny edges are in white color with a black background as

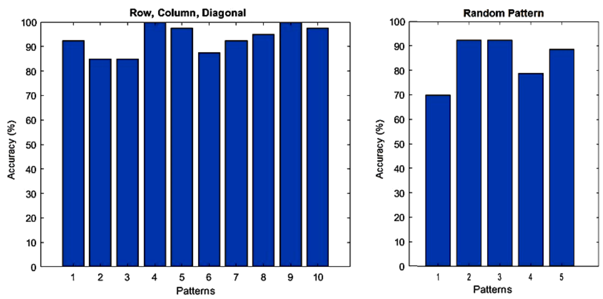

Fig. 8. Experimental Results.

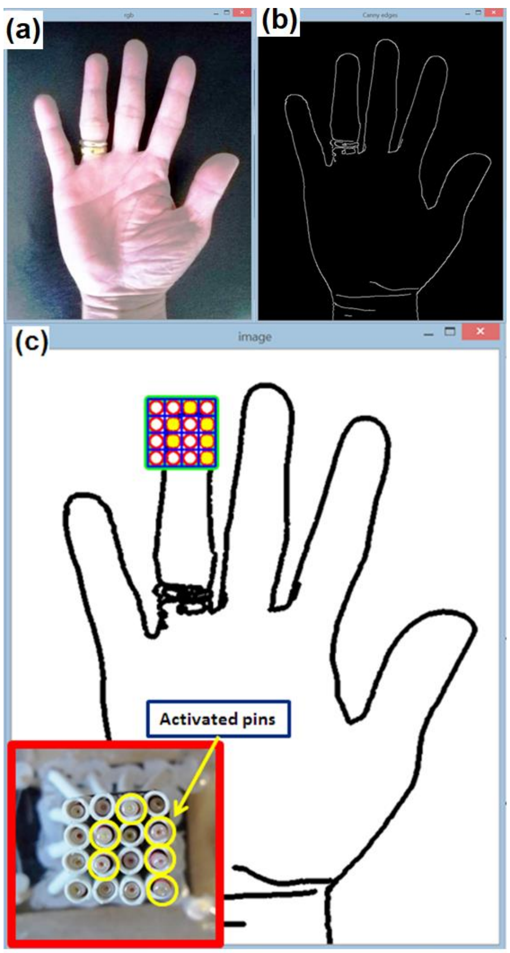

Fig. 9. Edge detection with moving ROI. a) RGB image of a hand, b) Canny edge image of Fig. 9a, and c) inverted Canny edge image with fingertip tactile matrix simulator and with corresponding activated tactile pins.

shown in Fig. 9b. We inverted the Canny edge image of Fig. 9b, as shown in Fig. 9c, because the tactile simulator detects black color edges as an 'up' signal. We also thicken the lines using Hough transform function in OpenCV. The activated pins, as shown inside the red box of Fig. 9c, correspond to the activated pins with the fingertip tactile matrix simulator at the tip of the ring finger. Moreover, this simulator can be applied to binary image of a color-filled regular polygon that gives the perception of touching a surface area instead of an edge.

5. CONCLUSION AND FUTURE DIRECTION

In this study, we developed two 4x4 tactile displays using miniature commercial off-the-shelf (COTS) DC solenoids. Prototype 1 can be used to study humans' ability to recognize Braille-like patterns through hand exploration. Prototype 2 is a fingertip tactile device based on prototype 1 with a miniaturization adapter that reduced the tactile surface area by 8 times (from 2,500 mm^2 to 289 mm^2) to study tactile pattern recognition using fingertip. A 4x4 tactile display simulator with an edge detection algorithm coupled to Prototype 2 enabled the user to feel the edges of an image. Aside from displaying Braille-like patterns, the actuators of the tactile display prototypes can be programmed to vibrate at different frequencies. We argue that the prototypes presented in this study could be useful for telerobotics, gaming applications, Virtual Reality (VR), tactile perception, and texture recognition.

6. ACKNOWLEDGMENTS

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7. REFERENCES

Benali-Khoudja, M., Hafez, M., Kheddar, A. (2007). VITAL: An electromagnetic integrated tactile display. Displays 28(3), 133-144.

Besse, N., Rosset, S., Z´arate, J. J., Ferrari, E., Brayda, L. & Shea, H. (2018). Understanding Graphics on a Scalable Latching Assistive Haptic Display Using a Shape Memory Polymer Membrane. Haptics IEEE Transactions, vol. 11, no. 1, pp. 30-38.

Bliss, J. C., Katcher, M. H., Rogers, C. H. and Shepard, R. P. (1970, March). Optical-to-tactile image conversion for the blind. IEEE Trans. Man-Mach. Sys., vol. 11, no. 1,pp. 58–65.

Chouvardas, V. G., Miliou, A.N., Hatalis, M.K. (2005). Tactile display applications: a state of the art survey. Proceedings of the 2nd Balkan Conference in Informatics, pp. 290-300.

Collins, C. (1970). Tactile Television-Mechanical and Electrical Image Projection. IEEE Transactions on Man-Machine Systems, vol. 11, no. 1, pp. 65-71.

DC Solenoid (2022). Retrieved Mar 3. 2022, from https: https://www.amazon.co.uk/DC-Solenoid-Electromagnet-SODIAL-Actuator/dp/B01GZWMSE2

Dot pad (2018). Dot pad: tactile graphic & braille display for the visually impaired. Retrieved March 3. 2022, from https://www.facebook.com/watch/?v=1633029773479398

Ide, M., Yaguchi, A., Sano, M., Fukatsu, R., & Wada, M. (2019). Higher Tactile Temporal Resolution as a Basis of Hypersensitivity in Individuals with Autism Spectrum Disorder. Journal of Autism and Developmental Disorders, 49:44–53.

Ikei, Y., Wakamatsu, K. and Fukuda, S. (1997). Vibratory tactile display of image-based textures. IEEE Computer Graphics and Applications.

Kappassov, Z., Corrales, J.-A., & Perdereau, V. (2015). Tactile sensing in dexterous robot hands – Review. Robotics and Autonomous Systems, Elsevier, 74, Part A, pp.195-220.

Kwon, D.-S., Yang, T.-H., Cho, J.Y. (2010, July). Trend & prospects of haptic technology in mobile devices. Symposium on Industrial Electronics (ISIE), IEEE, pp.3778–3783,

Kyung, K.-U. and Lee, J.-Y. (2009). Ubi-Pen: A haptic interface with texture and vibrotactile display. IEEE Computer Graphics and Applications, 29(1):24–32.

Lederman, S. J. and Klatzky, R. L. (2009). Haptic perception: A tutorial. Attention, Perception, & Psychophysics, 71(7), 1439-1459.

Rotard, M., Taras, C. and Ertl, T. (2008, March). Tactile web browsing for blind people. Multimedia Tools Appl. 37, 1, 53-69.

Russomanno, A., Xu, Z., O'Modhrain, S. and Gillespie, B. (2017). A pneu shape display: Physical buttons with programmable touch response. 2017 IEEE World Haptics Conference (WHC). New York,USA, 641–646.

Salsedo, F., Marcheschi, S., Fontana, M. and Bergamasco, M. (2011, June). Tactile transducer based on electromechanical solenoids. 2011 IEEE World Haptics Conference, pp. 581–586.

Sawada, H. (2016). "Tactile Display Using the Micro-vibration of Shape-Memory Alloy Wires and Its Application to Tactile Interaction Systems. In: Kajimoto H., Saga S., Konyo M. (eds) Pervasive Haptics. Springer, Tokyo.

Shen, Y., Liu, Y. and Kejie, L. (2000). Haptic Tactile Feedback in Teleoperation of a Multifingered Robot Hand. Proc. Third World Congress Intelligent Control and Automation, vol. 1, pp. 85-90.

Shimizu, Y. (1986). Tactile display terminal for visually handicapped. Displays, 7(3):116-120.

Szabo, Z. & Enikov, E.T. (2012). Development of Wearable Micro-Actuator Array for 3-D Virtual Tactile Display. Journal of Electromagnetic Analysis and Application, v.4.

Visell, Y. (2009). Tactile sensory substitution: Models for enaction in HCI. Interacting with Computers, vol. 21, no. 1–2, pp. 38-53.

Xie, Y., Chen, C.,Wu, D., Xi, W. and Liu, H. (2019, June). Human-Touch-Inspired Material Recognition for Robotic Tactile Sensing. Applied Sciences, 9(12):2537.