DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

HAPTIC DEVICE DESIGN FOR LINEAR BRAILLE CHARACTER REPRESENTATION

by
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İZMİR

HAPTIC DEVICE DESIGN FOR LINEAR BRAILLE CHARACTER REPRESENTATION

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by
Gözde GÜNDÜZ POYRAZ

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"HAPTIC DEVICE DESIGN FOR LINEAR BRAILLE CHARACTER REPRESENTATION"** completed by **GÖZDE GÜNDÜZ POYRAZ** under supervision of **ASST. PROF. DR. ÖZGÜR TAMER** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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HAPTIC DEVICE DESIGN FOR LINEAR BRAILLE CHARACTER REPRESENTATION

ABSTRACT

Touch is the most common sense for the human body. The human can discover and recognise approximately everything by touching it. In the proposed work, this property of human body is focused on to provide some capabilities to impaired people.

The proposed system is based on generation of different vibrational effects to present digital information to the user. In one embodiment of this system, digital letters are represented with vibrational effects. Therefore, distinguishable vibrational effects are generated for accurately detection of the digital information. The hybraille mouse system is explained as an example electronic device which comprises the proposed system.

Nowadays, the impaired people use external devices, such as Braille displays, to read digital information. However, these devices have some disadvantages, such as limited display area, expensive to repair them, seeming extra-ordinary…etc. Hence these cause additional obstacle to the impaired people and affecting their psychology negatively. Therefore, one of the purposes of this system is to provide reading and writing capability to the impaired people with the helping of standard looking devices. The system can be integrated to keyboard, mouse…etc.

In content of the thesis, the mouse, which is called as hybraille mouse, is focused on to explain the system in more efficient way. The end device will be cheap, easy to use, working with higher rate of accuracy, looking as usual devices. These properties of the system also supports the user psychologically, hence they will not discriminated from other people.

Keywords: Tactile, vibration, vibration motor, actuator, signal, haptic, braille

DOĞRUSAL BRAILLE ALFABESİ İÇİN HAPTİK CİHAZ TASARIMI

ÖZ

Dokunma, insan vücudu için en yaygın histir. İnsan, yaklaşık olarak her şeyi dokunarak keşfedebilir ve tanıyabilir. Önerilen çalışmada, engelli bireylere bazı yetenekler sağlamak için insan vücudunun bu özelliğine odaklanılmıştır.

Önerilen sistem, kullanıcıya dijital bilgi sunmak için farklı titreşimsel etkilerin üretilmesine dayanmaktadır. Bu sistemin bir düzenlemesinde, dijital harfler, titreşim etkileriyle temsil edilir. Bu nedenle, dijital bilgilerin doğru şekilde algılanması için ayırt edilebilir titreşim etkileri üretilir. Hybraille fare sistemi, önerilen sistemi içeren örnek bir elektronik cihaz olarak açıklanmaktadır.

Günümüzde, engelliler dijital bilgileri okumak için Braille ekranları gibi harici aygıtlar kullanıyorlar. Ancak, bu cihazların kısıtlı ekran alanı, onarımlarının pahalı olması, sıra dışı görünmesi gibi bazı dezavantajları var. Bu nedenle bunlar, engellileri etkileyen ek nedenlere ve psikolojilerinin olumsuz etkilenmesine neden olmaktadır.

Bu nedenle, bu sistemin amaçlarından biri, standart görünümlü cihazların yardımı ile engelli insanlara okuma ve yazma yeteneği sağlamaktır. Sistem klavyeye, fareye vb. entegre edilebilir. Tezin içeriğinde sistemi daha verimli bir şekilde açıklamak adına, hybraille faresi olarak adlandırılan, fare yapısına odaklanılmıştır.

Son cihaz, ucuz, kullanımı kolay, daha yüksek doğruluk oranıyla çalışan ve normal cihazlar gibi görünen bir ürün olacak. Sistemin bu özellikleri aynı zamanda kullanıcıyı psikolojik olarak da desteklemektedir, dolayısıyla diğer insanlardan ayırt edilmeyecektir.

Anahtar Kelimeler: Dokunsal, titreşim, titreşim motoru, aktüatör, sinyal, haptik, braille alfabesi

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CHAPTER ONE

INTRODUCTION

Nowadays, some types of electronic devices are developed to get the information via touching the surface of the devices. With the helping of this devices, the user can get any information from the device which is in field of biomedical, military applications, game consoles, mobile devices…etc.

For example, mobile devices convert digital information to mechanical movement and provide vibrational sensation to the user. The information which is obtained by the human and/or animal skin is send to central nerve system and processed there to provide recognition to the human and/or animal about its environment. Therefore the user can discover the environment by touching instead of seeing it.

In this project a vibrational electronic device is proposed. The electronic device provides different vibrational signals that are generated to provide sensation to the user instead of reading the information visually. Hence the user will feel the digital character via the electronic device. The electronic device will be a helpful solution for visually impaired people. With the helping of this device, reading and writing capability is provided these people. Therefore, they will easily gather information around them and are not discriminated from other people who can discover its environment by seeing.

1.1 Physiology of Tactile Sense

Touch is the one of the main five senses of the human and/or animals. This may be the oldest sensory system for human and/or animals from the beginning of their lives. It is the first sense which develops and responds stimulation in the uterus (R. Raisamo & J. Raisamo, 2011).

Theoretically, touch is the stimulus impacting the skin (Yann et al., 2012). It is essential for any human and/or animals to explore and recognise the things around it to learn how to survive. The skin of the human and/or animals sends necessary information to the central nervous system that provides exploitation and recognition to the human and/or animals in case of touching to solid or liquid objects. Therefore the locomotion system is initiated and causes body movements.

Different types of units exist stimulating a human and/or animals which are classified depending on their properties, i.e. nociceptors (detection of thermal and mechanical pain), thermoreceptors (for thermal information) and mechanoreceptors (for mechanical excitation) (Ramona, Francesco, Eric, Yves & Adnan, 2011).

In this project, mechanoreceptors are focused on since touch responses are created by mechanical stimulus. Cutaneous mechanoreceptors exist in the different layers of the skin where the mechanoreceptors detect many types of the mechanical stimuli. This variety of stimuli is matched by a diverse array of specialised mechanoreceptors that respond to cutaneous deformation in a specific way and relay these stimuli to higher brain structures(Yann et al., 2012).Figure 1.1 shows mail mechanoreceptors in the human skin (Lumen Learning, n.d.).

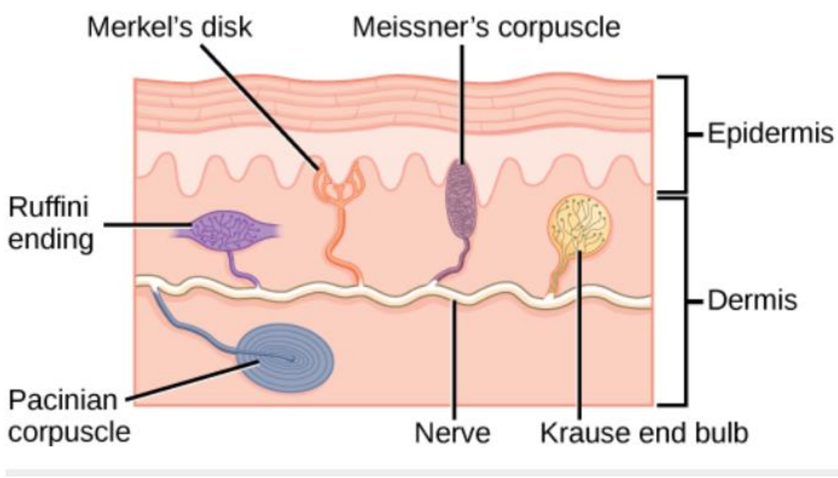


Figure 1.1 Four of the main mechanoreceptors in the human skin (Lumen Learning, n.d.)

Mechanoreceptors sense the touches which causes physical deformation at its plasma membranes. The plasma membranes include mechanically gated ion channels. These gates open or close corresponding to the touch, pressure or any other stimuli (Lumen Learning, n.d.). Figure 1.2 shows the structure of the organizations of the mechanoreceptors in the skin (Yann et al., 2012).

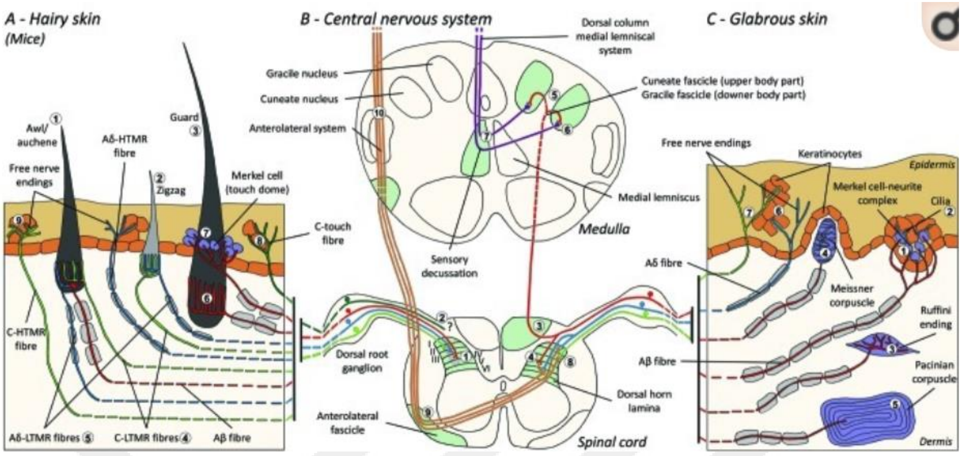


Figure 1.2 Organizations of the mechanoreceptors in the skin (Yann et al., 2012)

The number of receptors changes depending on respective part of the body surface. In somatosensory cortex of the brain, which processes the touch information, has a map of body surface. (Vox Media, 2015). Figure 1.3 shows human figure scaled depending on the amount receptors it has (Vox Media, 2015).

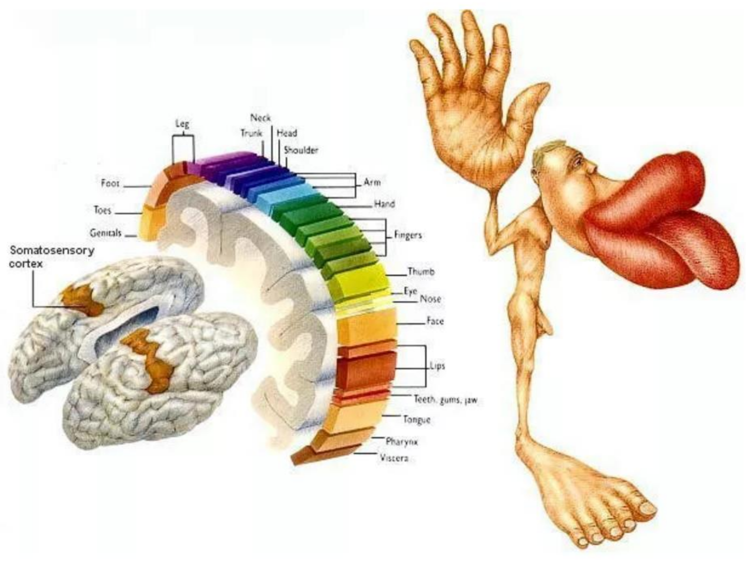
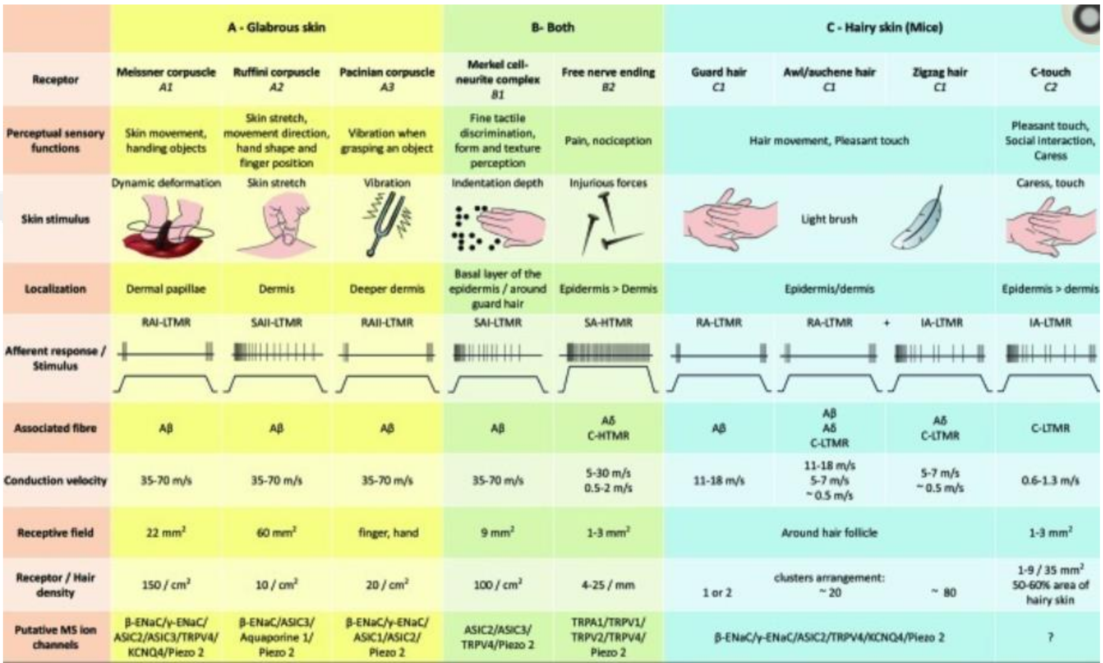


Figure 1.3 A human figure scaled depending on the amount of receptors it has (Vox Media, 2015)

Mechanoreceptors are classified into two categories depending on their speed of adaptation such as slowly adapting mechanoreceptors and fast adapting mechanoreceptors. Slowly adapting mechanoreceptors are sensitive to constant stimuli and rapidly adapting mechanoreceptors are sensitive to the short pulses (Yann et al., 2012). Figure 1.4 shows tactile receptors in mammals depending on some parameters.



	A - Glabrous skin			B- Both		C - Hairy skin (Mice)			
Receptor	Meissner corpuscle A1	Ruffini corpuscle A2	Pacinian corpuscle A3	Merkel cell-neurite complex B1	Free nerve ending B2	Guard hair C1	Awl/auchene hair C1	Zigzag hair C1	C-touch C2
Perceptual sensory functions	Skin movement, handing objects	Skin stretch, movement direction, hand shape and finger position	Vibration when grasping an object	Fine tactile discrimination, form and texture perception	Pain, nociception	Hair movement, Pleasant touch			Pleasant touch, Social interaction, Caress
Skin stimulus	Dynamic deformation	Skin stretch	Vibration	Indentation depth	Injurious forces		Light brush		Caress, touch
Localization	Dermal papillae	Dermis	Deeper dermis	Basal layer of the epidermis / around guard hair	Epidermis > Dermis	Epidermis/dermis			Epidermis > dermis
Afferent response / Stimulus	RAI-LTMR	SAII-LTMR	RAII-LTMR	SAI-LTMR	SA-HTMR	RA-LTMR	RA-LTMR +	IA-LTMR	IA-LTMR
Associated fibre	Aβ	Aβ	Aβ	Aβ	Aδ C-HTMR	Aβ	Aβ Aδ C-LTMR	Aδ C-LTMR	C-LTMR
Conduction velocity	35-70 m/s	35-70 m/s	35-70 m/s	35-70 m/s	5-30 m/s 0.5-2 m/s	11-18 m/s	11-18 m/s 5-7 m/s ~0.5 m/s	5-7 m/s ~0.5 m/s	0.6-1.3 m/s
Receptive field	22 mm²	60 mm²	finger, hand	9 mm²	1-3 mm²	Around hair follicle			1-3 mm²
Receptor / Hair density	150 / cm²	10 / cm²	20 / cm²	100 / cm²	4-25 / mm	1 or 2	clusters arrangement: ~20	~80	1-9 / 35 mm² 50-60% area of hairy skin
Putative MS ion channels	β-ENaC/γ-ENaC/ASIC2/ASIC3/TRPV4/KCNQ4/Piezo 2	β-ENaC/ASIC3/Aquaporine 1/Piezo 2	β-ENaC/γ-ENaC/ASIC1/ASIC2/Piezo 2	ASIC2/ASIC3/TRPV4/Piezo 2	TRPA1/TRPV1/TRPV2/TRPV4/Piezo 2	β-ENaC/γ-ENaC/ASIC2/TRPV4/KCNQ4/Piezo 2			?

Figure 1.4 Tactile receptors in mammals depending on some parameters (Yann et al., 2012)

According to study of (Ramona et al., 2011), the operating frequency for human perception is between 2 Hz and 500 Hz. The highest sensitivity is around 300 Hz for fast adapting mechanoreceptors. Figure 1.5 shows the schematic representation of the finger contact to the object surface (Ramona et al., 2011).

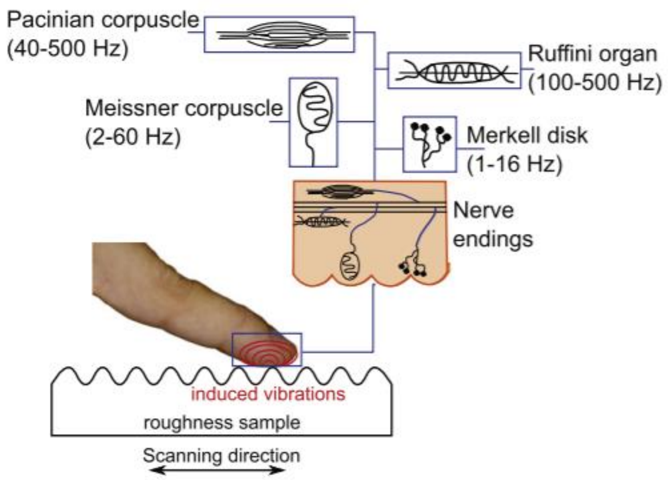


Figure 1.5 Schematic representation of the finger contact to the object surface (Ramona et al., 2011)

The most sensitive part of the human body for tactile sense is fingertips since higher density of the receptors exist in this part of the body. The small changes in the surface can be easily detected by the fingers. Therefore, the Braille can be detected quickly and correctly by both visually impaired and deaf people.

1.2 Tactile Display

Tactile display is a device which provides tactile sense to the human to acquire specific information such as temperature information, surface structure, written information…etc. can be accurately detected with the helping of these devices. Figure 1.6 shows classification of haptic terminologies (Yi, 2013).

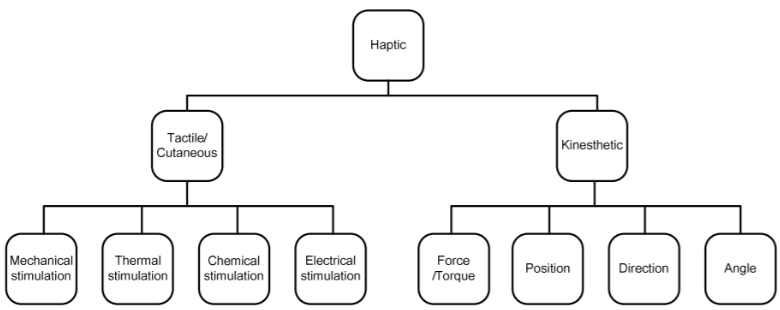


Figure 1.6 Haptic feedback terminologies (Yi, 2013)

The display system is classified into following main categories;

Temperature,
Pressure (mechanical energy),
Vibration (mechanical energy),
Electric field,

The tactile displays are widely used at text and graphics, military applications, virtual environment applications, medical applications, entertainment and educational applications, wearable devices…etc. (Vasilios G., Amanlia N. &Miltiadis K., 2005).For example, while playing a game in mobile, the user can get warning only with different vibration effect. Hence the user can detect in which situation he/she come across.

In this project, tactile system is developed for recognition of the text and this text can be easily read by the impaired people. Therefore, the visually or hearing impaired people can get the capability to explore and recognise the things around them without any need to see the things.

1.2.1 Vibration Mechanism

The tactile displays use vibration as a feedback mechanism to the user. Vibration motors or actuators are used for this this purpose.

The vibration is a force vector which has both magnitude and direction. It is important to take care of the direction of vibration to get best tactile feedback depending on the designed system needs. To get the best tactile sense, the direction of vibration should be towards the user and in the same plane with the applied force to the electronic device (Precision Microdrives, n.d.).

1.2.1.1 ERM (Eccentric Rotary Mass)

The most commonly used vibration motor is ERM (Eccentric Rotary Mass), but other electronic components are also used depending on the device needs. ERMs are generally used at vibration alert and haptic feedback mechanisms. Figure 1.7 shows some types of ERM actuators depending on their structure or shape (Precision Microdrives, n.d.).

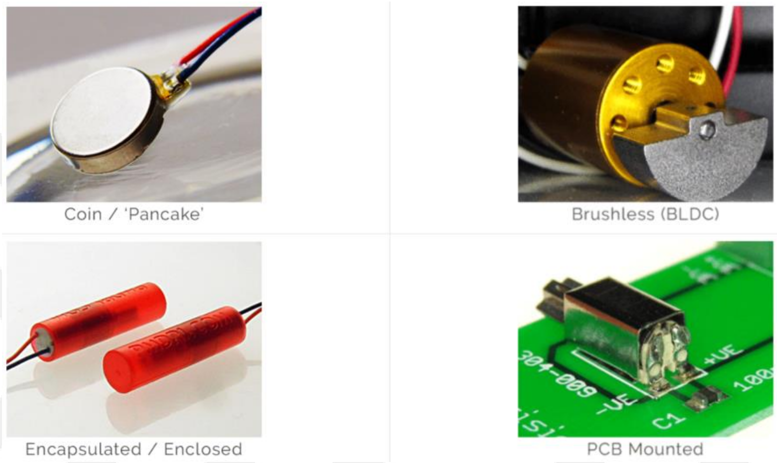


Figure 1.7 Some types of ERMs (Precision Microdrives, n.d.)

Please find below some technical fields at which ERMs are used;

Handheld medical instruments,

Pagers,

Automotive displays/dashboards,

Mobile phones,

Personal notification devices (i.e. watches, wristbands),

Tablet PCs,

Industrial tools/interfaces,

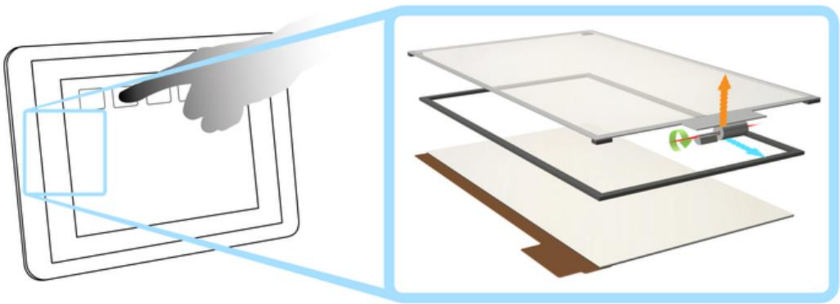


Figure 1.8 ERM in touch screen example (Precision Microdrives, n.d.)

In figure 1.9, internal structure of the ERM actuators are shown with respect to each existing component (Precision Microdrives, n.d.).

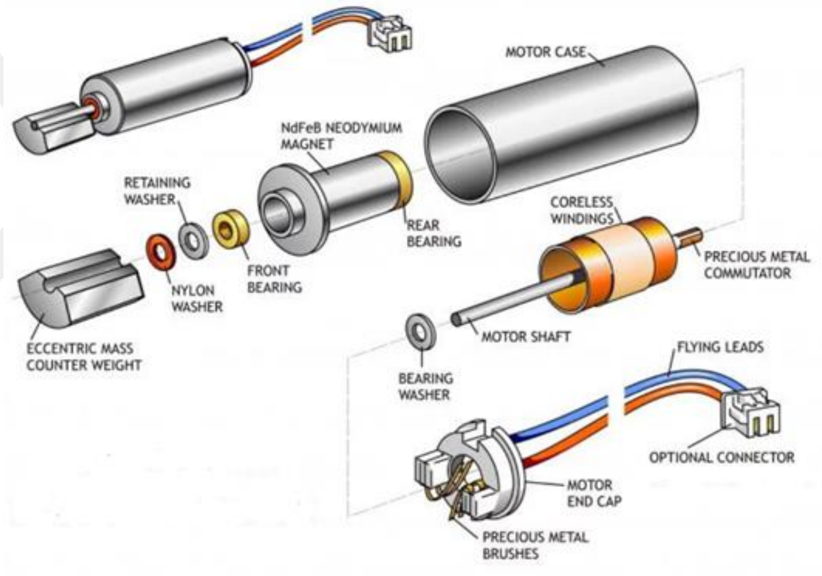


Figure 1.9 Schematics of the ERMs (Precision Microdrives, n.d.)

The miniature non-symmetric eccentric rotating mass is attached to the rotor of ERM. When the current applies to the motor, the motor starts rotating. However, due to the non-symmetric eccentric rotating mass, the small continuous displacements occur at the motor. The motor starts to move back and forth and this creates vibration. Figure 1.10 shows vibration direction of ERM actuator (Precision Microdrives, n.d.).

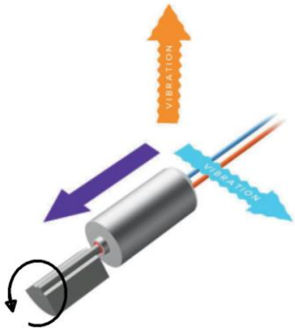


Figure 1.10 Vibration direction of the ERM (Precision Microdrives, n.d.)

The non-symmetric eccentric rotating mass creates centrifugal force on motor body which causes vibration in two axes.

$$f_{vibration}=\frac{Motor_{RPM}}{60} \tag{1.1}$$

$$F_{vibration} = mxrxw^2 \tag{1.2}$$

where

$f_{vibration}$ is the frequency of the motor

$F_{vibration}$ is the centrifugal force on the motor

m is the mass of the eccentric weight,

r is the mass offset distance,

w is the speed of the motor (1/rad)

$$w=2\pi f \tag{1.3}$$

Where m is the mass, r is the non-symmetric eccentric rotating mass distance and ω is the angular speed of the motor. Since m and r are physical parameters of the ERM module, the single parameter that can change the centrifugal force F is the angular frequency ω of the motor and therefore motor speed is changed. When the motor speed changes, vibration frequency which directly depends on the motor speed also changes (Yangyi, 2013). Table 1.1 shows some specifications for ERM vibration motors produced by the Physik Instrumente.

Table 1.1 Some example specifications for ERM vibration motors (Physik Instrumente, n.d.)

Model	Diameter	Voltage	Speed (rpm)	Amplitude (G)
303-103	3.2 mm	3 V	15.5	0.9
304-005	4.5 mm	1.5 V	11	0.5
304-002	4 mm	3 V	12.5	0.7
304-108	4 mm	3 V	12.3	1.18
304-121	4.6 mm	3 V	17.5	0.62
306-101	6 mm	3 V	11.5	2.8
306-002	6 mm	1.5 V	9	1
306-103	6 mm	3 V	14.3	4.51
307-002	7 mm	1.5 V	13	6.4
307-103	8.7 mm	3 V	13.8	7
307-103	13.7 mm	3 V	13.4	7
308-106	8 mm	3 V	7.5	9.5
312-107	12 mm	3 V	6.4	14.3
320-105	20.4 mm	3 V	6.1	15.9

Since the ERM is a DC motor, it is driven by a DC current. Therefore to change the angular speed of this motor, a switching circuit is needed to turn on and off the motor depending on the system needs. Hence the motor is controlled with Pulse Width Modulation (PWM) signal that rapidly changes the angular speed of the motor by turning on and off with a specific duty cycle wherein the duty cycle is the ratio of high level (ON state) of signal within one cycle. The duty cycle provides soft transition between ON state and OFF state of the motor.

The PWM is also used to adjust the intensity of the vibration. The duty cycle of the PWM signal which drives the ERM proportionally changes the frequency and effective amplitude of the vibration. With the helping of these two parameters, different tactile sense can be obtained to generate distinguishable sense over the tactile device. Figure 1.11 shows some PWM signals with different PWM ratio (Analog IC Tips, 2017).

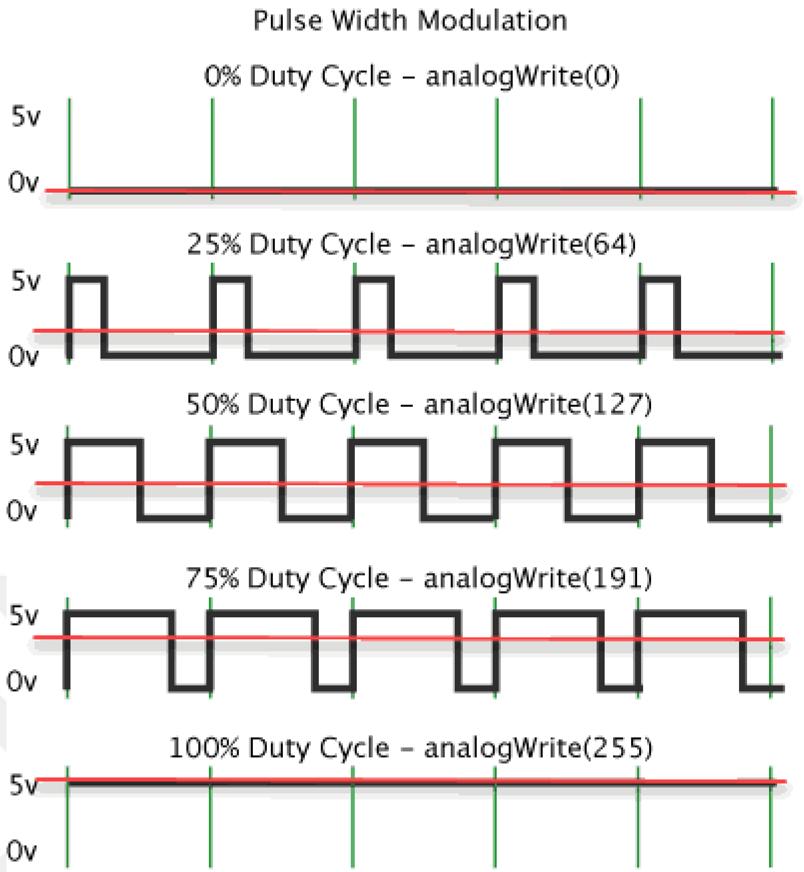


Figure 1.11 PWM signals with different duty cycles (Analog IC Tips, 2017)

The other way to get different tactile senses is to vary applied voltage to the motor. However this voltage should be within the specified voltage range for the motor operation. The speed of the motor can be changed by changing the applied voltage. This way is limited with comparing to getting a different vibration by changing the frequency and effective amplitude. By changing frequency and effective amplitude, more precise sense can be sensed.

For a specific case such as sharper sense, the immediate stop of motor is needed. Therefore, reverse polarity voltage is applied via H-bridge motor driver for short period of time before turning off the motor. With the helping of this process, immediate stop of the motor is provided. The reverse polarity voltage opposes existing kinetic energy at the non-symmetric eccentric rotating mass, hence further vibration production is prevented.

By the way, if the start voltage is adjusted as a little higher than the specified operating voltage of the motor is applied, then the immediate start of the motor is provided as opposite operation of the above.

With the helping of the combination of an H-bridge circuit and a variable voltage source, the on and off times of the ERM motor can be optimized. The application of high voltage will provide increase the rate which causes eccentric mass reaches the optimal speed for desired vibration generation. Since the eccentric rotary mass accelerates, the voltage will decrease to the its optimal operating voltage to sustain the vibration at a desired rate. Then, a brake voltage may be supplied through the H-bridge circuit to decrease the speed of the motor down at a faster rate when turning off the vibration (SomaticLabs, 2016). Figure 1.12 shows driving voltage characteristic for ERM actuator including overdrive and brake voltages.

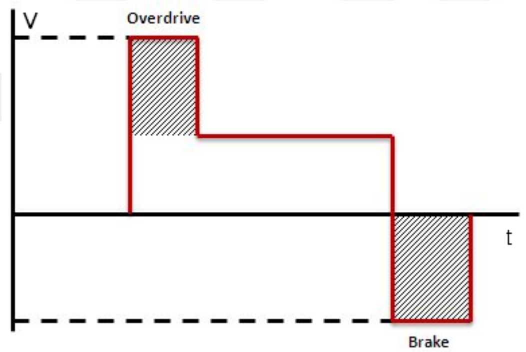


Figure 1.12 Driving voltage characteristic for ERM including overdrive and reverse voltages

Because of the moistening involved with the respect to large mass of the device, these motors try to have limited frequency response and get old rapidly. These motors have high performance between units, over the life of a battery, and over the life of a device.

The use of ERM is easy way to create vibration or alert to the user. However, it is not suitable to generate sharp tactile feedback since it responds slowly (Yi, 2013).

1.2.1.2 Linear Resonant Actuator (LRA)

While ERMs use DC motor for vibration, LRAs (Linear Resonant Actuators) relies on AC drive voltage. LRAs include magnet, voice coil, wave spring and moving mass.

Figure 1.13 and Figure 1.14 shows internal structure of both Y-axis LRA and Z-axis LRA (Texas Instruments E2E Support Forum, 2016).

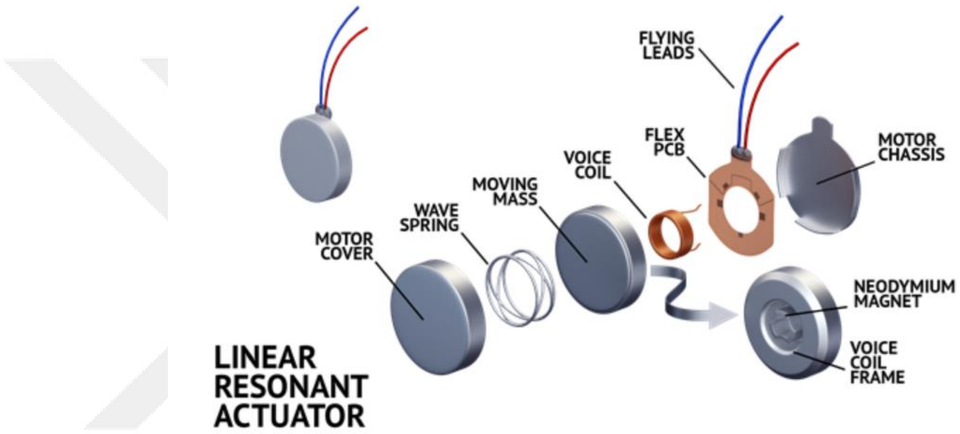


Figure 1.13 Schematics of Y-axes LRA (Texas Instruments E2E Support Forum, 2016)

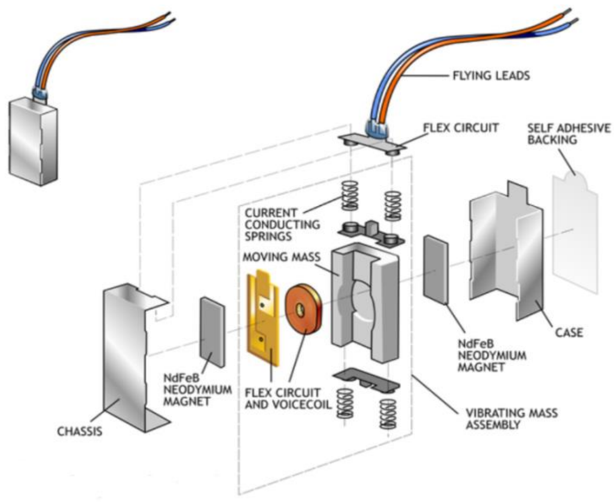


Figure 1.14 Schematics of Z-axes LRA (Texas Instruments E2E Support Forum, 2016)

They are widely used at below listed technical fields without any limitation and touch screen use example of LRA is shown in Figure 1.15 (Precision Microdrives, n.d.).

Touchscreen
Car dashboard button panel
Mobile phones

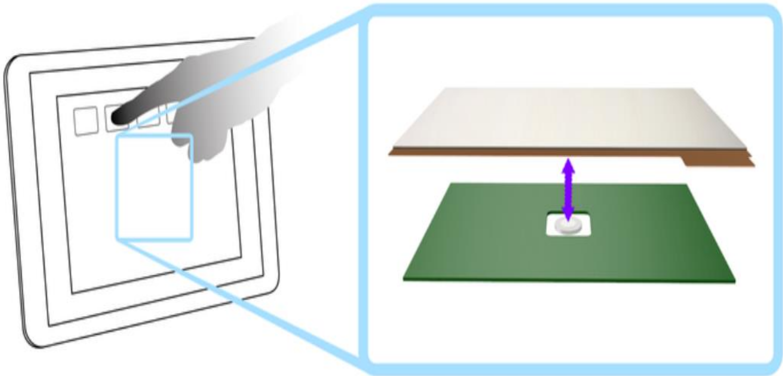


Figure 1.15 LRA in touchscreen example (Precision Microdrives, n.d.)

When AC voltage is supplied to the LRA, the voice coil produces a magnetic field. This magnetic field applies a force to moving mass which is attached to the wave spring placed at the centre of the vibration module. While the voice coil is stationary, the wave spring moves back and forth according to the direction of the magnetic field. This movement causes vibration depending on the frequency and amplitude of the supplied electrical signal.

Since the mass is restricted to move back and forth, the vibration produced by the LRA module is in one axis. The direction of vibration Y-axis or Z-axis depends on the type of the LRAs. Figure 1.16 shows vibration direction of Y-axis and Z-axis LRA actuators.

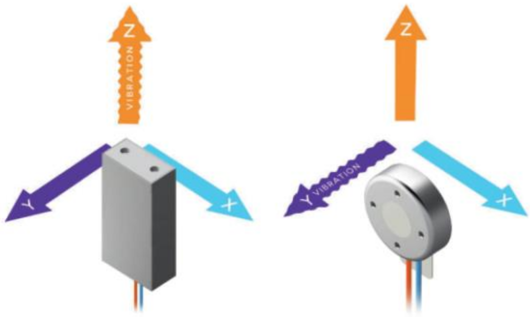


Figure 1.16 Vibration directions of the LRAs (Precision Microdrives, n.d.)

The operation of the LRA is like creating music in a loudspeaker. The displacement at speaker cone provides audio waves. However, the speaker cone can operate at wide range of frequencies; however the LRA is tuned to its resonant frequencies for less power consumption (Precision Microdrives, n.d.).If the LRA is driven with the frequency, which is different than its resonant frequency, the performance of the LRA is highly reduced and inefficient operation occurs. By the way, the resonant frequency of the LRA can be changed since the elasticity of the spring may be changed when the LRA is aged.

The LRA consumes less power than ERM since it has short start-stop times and it produces less noise because of not having spinning mass. This quick response of the LRA provides immediate vibration generation. In ERM, the vibration is generated when the motor reach its operation speed and even the motor is driven by overdrive voltage, it takes some time for motor to reach its operation speed.

However, the stop time of the LRA is longer than the ERM. The LRA can needs to 300ms to stop vibrating since its property of storage of kinetic energy in the internal spring during operation. Thankfully, an active braking mechanism can also be used for the LRA with the helping of a 180-degree phase shift of the AC signal provided to the actuator, the vibration can be stopped very quickly, approximately 10ms, via a force which is opposite to the oscillation of the spring (SomaticLabs, 2016).

Although the input voltage to ERM affects both vibration amplitude and frequency, the voltage and frequency can be separated in LRA. Since the coil is driven by an AC current modelling the desired frequency and amplitude of vibration, the frequency and amplitude may be independently modified. This provides an advantage when generating different vibration signals since voltage and frequency of the LRA can be adjusted separately.

Table 1.2 shows some example specifications for LRA vibration modules produced by Precision Microdrives.

Table 1.2 Some example specifications for LRA vibration modules (Precision Microdrives, n.d.)

Model	Size	Rated Voltage	Rated Frequency	Rated Current	Typical Amplitude
NFP-ELV0832A	φ=8mm T=3.2mm	AC 1.8Vrms	235Hz	53mA	1.63G
NFP-ELV1036A	φ=10mm T=3.6mm	AC 2.0Vrms	205Hz	75mA	1.85G
NFP-ELV1030AC1	φ=10mm T=3.0mm	AC 2.0Vrms	205Hz	75mA	1.7G
NFP-ELV1030AL	φ=10mm T=3.0mm	AC 2.0Vrms	205Hz	75mA	1.72G
NFP-ELV1030AL	φ=10mm T=3.0mm	AC 2.0Vrms	205Hz	75mA	1.72G
NFP-ELV1030AL	φ=10mm T=3.0mm	AC 2.0Vrms	205Hz	75mA	1.72G
NFP-ELV1030AC2	φ=10mm T=3.0mm	AC 2.0Vrms	205Hz	75mA	1.72G
DMJBRN1030BK	φ=10mm T=3.0mm	AC 2.0Vrms	205Hz	90mA	1.72G

1.2.1.3 Piezoelectric Actuators

Piezoelectric actuators are devices which produces mechanical displacement in case of electric voltage supply. The piezoelectric element shrinks and expands in case of voltage supply. It also has inverse operation such as electric generation in case of mechanical displacement.

Figure 1.17 and Figure 1.18 show structure of piezoelectric effect and inverse piezoelectric effect.

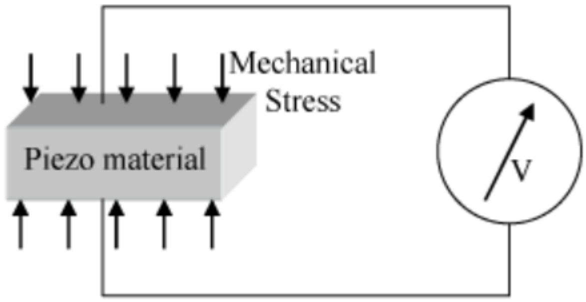


Figure 1.17 Piezoelectric effect

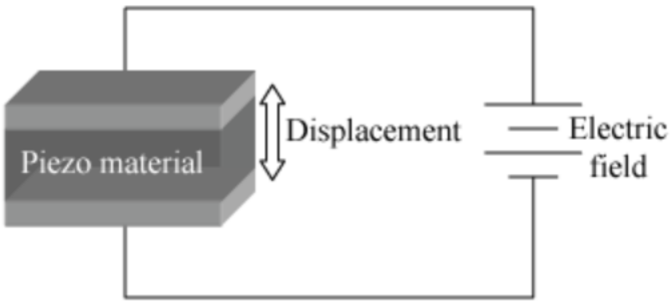


Figure 1.18 Inverse piezoelectric effect

Piezoelectric actuators are widely used as high precision vibration mechanism since it can generate small mechanical displacement with high speed because of its advantages such as ease of use and stable displacement. However, it also has some drawback since it needs high voltage, up to a few hundred volts (Y.Q. Fu, J.K. Luo, A.J. Flewitt &W.I. Milne, 2012, s. 291-336). Therefore, it causes some limitation to be used at battery-powered and/or small electronic devices.

Table 1.3 shows specifications of rectangular benders produced by Physik Instrumente (Physik Instrumente, n.d.).

Table 1.3 Specifications of Rectangular benders produced by Physik Instrumente

Model	PL112.10	PL122.10	PL127.10	PL128.10	PL140.10	Unit	Tolerance
Voltage range	0 to 60 (±30)	0 to 60 (±30)	0 to 60 (±30)	0 to 60 (±30)	0 to 60 (±30)	V	
Displacement	±100	±310	±450	±450	±1000	µm	±20 %
Remaininglength L_F	12	22	27	28	40	mm	
Length L	18	25	31	36	45	mm	±0.5 mm
Width W	9.60 ±0.2	9.60 ±0.2	9.60 ±0.2	6.15 ±0.1	11.00 ±0.2	mm	
Height TH	0.67	0.67	0.67	0.67	0.55	mm	±0.1 mm
Blockingforce	±2.1	±1.25	±1.1	±0.55	±0.5	N	±20 %
Electricalcapacitance	2 × 1.1	2 × 2.5	2 × 3.4	2 × 1.2	2 × 4.1	µF	±20 %

The piezoelectric element may be in a shape of coin or rectangular strip, which is also called as bender. Piezoelectric disks deform vertically and can be used for z-axis vibration. Piezoelectric benders can be mounted directly to a “floating” touch screen to vibrate only the screen. Piezoelectric benders can also be mass mounted in a small module that can be mounted to the device's case or PCB to provide vibration for the whole device.

Figure 1.19 shows the structure and form change of piezoelectric actuator for vibration operation (NFP Motor, n.d.).

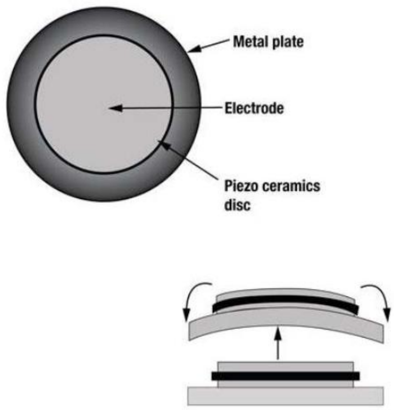


Figure 1.19 Form change of coin and strip type piezo actuators

Piezoelectric actuators are more accurate with respect to both ERMs and LRAs since they can vibrate at a wide range of frequencies and amplitudes that can be independently controlled using the driving AC voltage. Since the vibration does not rely on the resonant frequency of a spring as LRA, the frequency may be modified independently without a significant loss of efficiency.

Generally available piezoelectric actuators in market have a start time of nearly 14 ms, which barely outperforms most commercially available LRA actuators. More importantly, a piezoelectric actuator can typically produce a highly stronger vibration, and hence allowing larger devices to provide richer haptic effects that propagate through a larger portion of the device body. Although piezoelectric actuators require a much higher voltage for their operation, the current consumption (and overall power consumption) is less than with most of the LRA actuators.

1.2.1.4 Tactors

Tactors are acoustic transducers that generate sinusoidal vibrations with the frequency of 200-300 Hz to the skin. This frequency range is enough to activate Pacinian corpuscles. Tactors operate well at this specific frequency range and its optimum operation frequency is 250 Hz. Figure 1.20 shows some tactor models (EAI Engineering Acoustic Inc., n.d.).

Figure 1.20 Some types of tactors (EAI Engineering Acoustic Inc., n.d.)

Tactors are driven by AC voltage and generates a vibration with respect to the frequency and amplitude of the driving signal. Unlike an LRA, tactor vibrates with the helping of a moving “contactor” that oscillates in and out of the housing of the device. As a result, the vibrations from the tactor are delivered on a single point of the skin instead of delivering the vibration across the entire device. The enclosure of the tactor causes the vibration to be isolated to a small surface area, providing haptic interfaces constructed from tactors to utilize effects reliant on the localization of vibrations by user (EAI Engineering Acoustic Inc., n.d.). Table 1.4 shows specifications of some tactors produced by EAI Engineering Acoustic Inc. (EAI Engineering Acoustic Inc., n.d.).

Table 1.4 Specification of some tactors produced by EAI Engineering Acoustics Inc.

	C-2	C-3	EMR	EMS^2	C2-HD	C2-HDLF	Mini PiezoTac	PiezoTac	CLF-AN
Operating Frequency (Hz)	200-300	180-320	80-140	60-100	160-260	50-160	180-300	180-300	20-80
Optimum Frequency (Hz)	250	240	115	90	230	120	275	275	40
Max Peak to Peak Displacement when loaded mm (inches)	0.8 (-0.031)	0.55 (-0.022)	0.7 (-0.028)	2 (-0.079)	0.9 (-0.035)	1.3 (-0.052)	0.8 (-0.031)	0.8 (-0.031)	1.1 (-0.043)
Height	0.31"	0.25"	0.40"	0.75"	0.50"	0.50"	0.19"	0.21"	1.32"
Diameter or L x W	1.2"	0.8"	1.0"	1.9"	1.2"	1.2"	1.59" x 0.53"	1.88" x 0.86"	1.25"
Weight	17 g	8 g	5 g	24 g	25 g	30 g	5 g	10 g	98 g
Application W = Wearable S = In-Seat	W	W	W	W/S	S	W/S	W	W	S

1.2.1.5 Electrostatic Haptics

An electrostatic haptic is a technology which provides tactile feedback to the human skin without using any moving parts. The basis of this technology is electro vibration which provides broad range of tactile senses with the helping of electrostatic friction between surface of an electronic device and human skin. This surface friction is felt as a rubbery sensation (Olivier, Ivan, Ali & Chris, 2010). Figure 1.21 shows Tesla touch operating principle (Olivier et al., 2010).

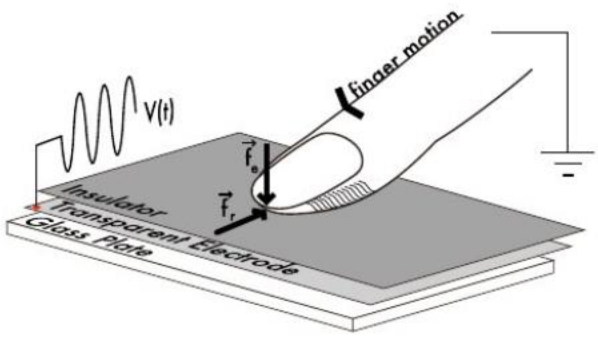


Figure 1.21 Tesla touch operating principle (Olivier et al., 2010)

The surface of the electronic device is coated with the insulating layer which has capability to keep electric charges and the touch of human causes capacitance change in that location since outer surface and fluid in finger form dielectric layer of the capacitor. The touch causes electric change drawn from the contact point to the human finger when the alternating voltage is applied. The electrostatic force deforms the human finger and this causes friction sensation while drawing finger over the device surface. Figure 1.22 shows Tesla touch electro vibration technology structure (Olivier et al., 2010).

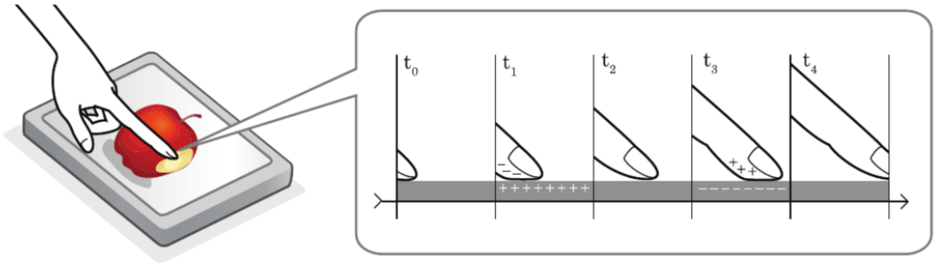


Figure 1.22 Tesla touch electro vibration technology structure (Olivier et al., 2010)

The electro vibration technology can be used at wide range of application since it is energy efficient, fast, dynamic...etc. It is an effective solution for application including multi touch and devices with any size and shape.

1.3 Braille Alphabet

Braille alphabet was invented by Louis Braille and Charles Barbier in 1821 to provide a secret communication method for the French Army without using light or sound.

Then, this alphabet is used for different objection to provide reading and writing capability to visually impaired people. This alphabet comprises 6 dots to represent all characters such as numbers, alphabet, punctuations…etc. These 6 dots are placed as 3 rows and 2 columns like 6 on a die. 64 symbols can be represented with the helping of Braille alphabet since 2^6 is equal to 64. Figure 1.23 shows the structure of Braille cell comprising 6 dots placed as 3 rows and 2 columns.

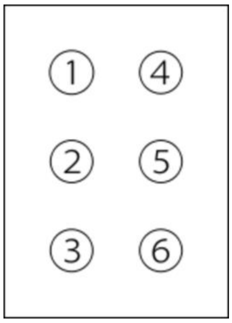


Figure 1.23 Braille cell comprising 6 dots

The Braille code exists for every language such as Turkish, English, French…etc. The Braille representations of some characters are shown in Figure 1.24 (Braille Authority, n.d.).

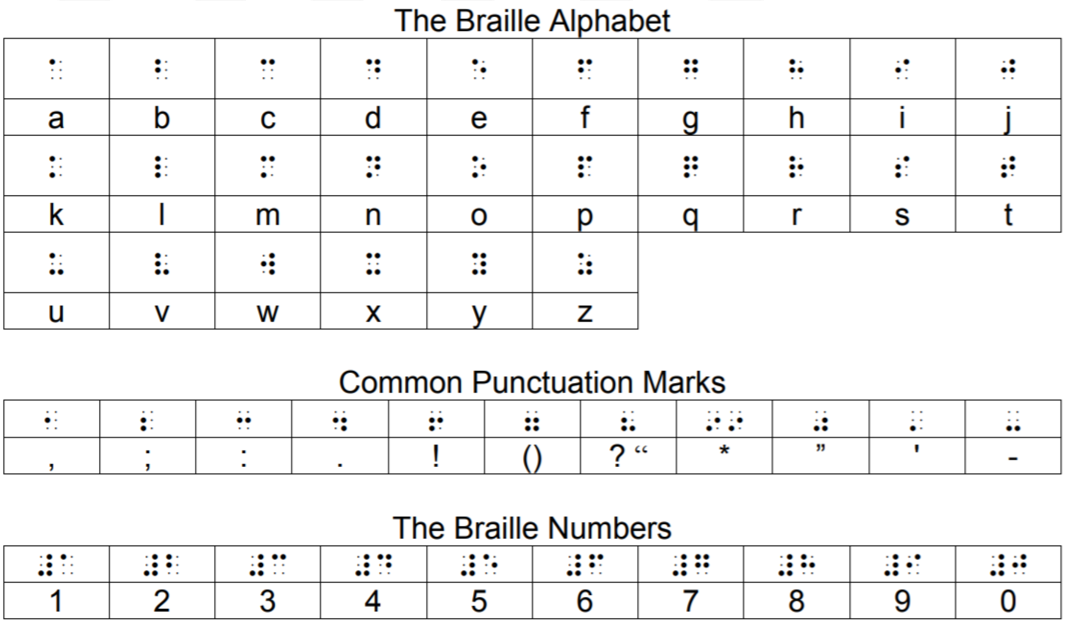


Figure 1.24 Braille representations of some characters

Since the Braille representations of numbers or any other characters are also available, texts in books, magazines, reports or any other writable information is can be represented with the Braille characters. This provides capability to write complex information such as math formulas, music notes, computer notations…etc.

Braille alphabet is developed for hard printed surfaces. A visually impaired person needs to feel 6 dots of the braille cell at the same time in order to read the character one by one to extract complete sentences or meaning by moving his/her finger over the Braille cells. Figure 1.25 shows Braille characters printed surface.

Figure 1.25 Printed texts with Braille characters

1.3.1 Braille Displays

The Braille alphabet method provides an access to written information for visually impaired people. Nowadays, higher number of publications is in electronic form. Hence, electronic Braille generators are needed to be developed to read digital Braille text. These devices convert digital Braille cells into tactile Braille for the visually impaired people.

There are different types of Braille generators depending on their method to convert digital data to tactile Braille.

1.3.1.1 Linear Braille Displays

The Braille cells are read by moving a finger from left to right. The initial cell starts to be refreshed while user is reading the final letter in the single line displays.

Each of the dots at Braille cells are controlled by actuators which are raising the dots vertically to provide the user senses these dots while moving his/her finger.

Solenoid actuators, piezoelectric actuators or pneumatic actuators are widely used as actuating mechanism for these types of displays.

Perkins Brailler is the most widely used refreshable Braille generator which is shown in Figure 1.26. It comprises single line and from 8 to 80 Braille cells (Maham, Nida, Umar & Faizan, 2016).

The other refreshable Braille generator, which is widely used, is Bristol Braille. It comprises 4 lines and 28 Braille cells in each line. The dots are driven by totally 672 actuators. Therefore it is expensive and may be broken easily due to friction while raise and fall of the dots. This has more disadvantageous than Perkins Brailler (Maham et al., 2016).Figure 1.26 shows linear refreshable braille display (Maham et al., 2016).

Figure 1.26 Linear refreshable braille display (Maham et al., 2016)

1.3.1.2 Rotating Braille Display

This type of Braille display has rotating wheel which contains cells over its circumference. It can show long length of Braille character by using less actuator. For example, 6 dots Braille cell can be shown with 3 actuators and 8 dots Braille cell can be shown with 4 actuators.

The user put his/her finger to the reading area which is on the top of the rotating Braille display. The rotation angle is controllable via software and the user feels as touching a static line of Braille text moving under his/her finger (Maham et al., 2016).Figure 1.27 shows mechanism of rotating braille display (Maham et al., 2016).

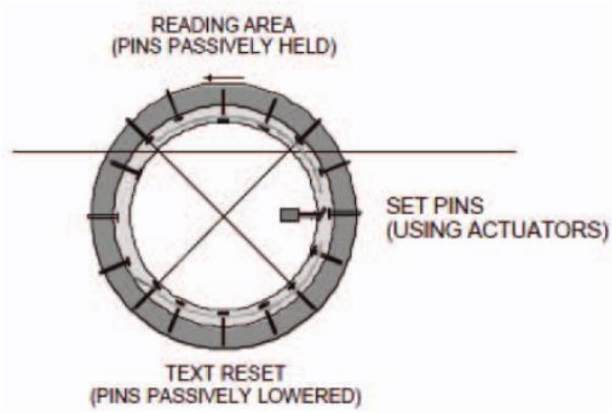


Figure 1.27 Mechanism of rotating Braille display (Maham et al., 2016)

Since the system shows the Braille cells with rotation of the Braille display, this significantly reduces size of the system. Additionally using less actuator provides cost efficiency to this system.

1.3.1.3 Panda Braille Displays

The system was developed by the VIT University students at India. It is based on electrocutaneous stimulation to provide perception of the dots of the Braille cells. Each dot at the Braille cell is represented by an electrode to which impulse response is applied (Maham et al., 2016).

When the user finger touches the surface, the system is completed and current flow occurs. The current is enough for the user to read the Braille cell without any damage.

Figure 1.28 shows Panda braille display developed by VIT University students (Maham et al., 2016).

Figure 1.28 Panda braille display developed by VIT University students (Maham et al., 2016)

This device is more energy efficient, cost efficient and less complex than previous technologies. It is portable due to being a light weight system. However, this Brailler comprises a single Braille cell and this may be disadvantageous for the user since he/she can't move his/her finger across the Braille cells for reading operation (Maham et al., 2016).

Table 1.5 Comparison of the braille displays

Brailler Type	Mechanism	Design Complexity	Reliability	Cost
Linear Brailler	Braille cells are along the length of the device	*	***	***
Rotating Brailler	A rotating wheel with braille cells along the circumference	***	**	**
Panda Brailler	Electrocutaneous stimulation	***	Insufficient information	*

All of these Braille displays are external electronic devices for reading Braille characters which are in form of digital text. Also they do not provide writing capability to the users. Therefore, a Hybraille system is proposed in content of this work to provide both reading and writing capability to the visually impaired people.

This system will be a cost efficient solution since it does not require additional electronic device and it can be integrated to the mouse, keyboard…etc.

In addition to Braille displays, other prior art studies exist in order to guide impaired people with the helping of haptic technologies. These are generally based guide or obstacle prevention for visually impaired people.

In one of the study, the guide is developed to assist blind people while navigation to the selected destination without sound instructions. In this system, guide is provided by different vibration patterns with the helping of tactor. The system is integrated into a wrist for the blind people (Slim, Christophe, Tiago, Hugo & Joaquim, n.d.).

In another study, mobile guide system is developed in order to prevent blind people from any obstacles while visiting the museum. The tactile and voice feedback system are combined to increase the efficiency of the system. With the helping of this system, blind people will be integrated with other visitors. RFID tags attached to all artworks and the user will be informed about them while walking. The tactile feedback helps blind people to detect any obstacle within the range of 10 to 90 cm and with 35 degree angle. In case of obstacle presence, the user will be warned by continuous or discontinuous vibration pattern. Two actuators are used in this system and they are wearable to two fingers in order to discriminate which of the actuators vibrate (Giuseppe, Barbara & Fabio, n.d.).

In another study, some of the systems for blind people are analysed. One of the systems is laser cane which contains laser and actuator. The actuator vibrates with higher or lower frequency corresponding to the distance sensed by the laser system. In addition to tactile system in laser cane, this paper also discloses refreshable Braille displays to present digital information to the blind people. However, these devices are expensive and difficult to repair them. They have limited display area (Vincent, n.d.).

In another study, writing capability provided for the visually impaired people over touch screen. Each of the left and right side of the screen is divided into three parts which represents Braille dots. The user is expected to move the dots to corresponding parts of the screen to write Braille character. After moving the dots, the user will touch the screen as double-tap to enter the letter he/she writes (Joao, Tiago, Hugo, Jaoquim & Daniel, n.d.).

These prior art system generally based on obstacle prevention for visually impaired people. Even one of the prior studies disclose a system for writing a Braille character, the system does not provide a capability of reading Braille character by touching the device surface.

In the proposed study in content of this thesis, the visually impaired people will be able to read and write digital information by touching the hybraille system. The system can be integrated to some electronic device such as mouse, keyboard, mobile device…etc. Therefore, the device is portable and looking as usual device in order to provide some additional advantages to the visually impaired people both psychologically and daily usage.

In chapter two, the proposed hybraille system and its electronic structure are disclosed over mouse as one of the embodiment of the system. The properties and advantages of electronic components, which are used in hybraille system, are discussed. The generated vibration effects are also disclosed in this part of the thesis.

In chapter three, the test system comprising learning part and test part for obtaining the accuracy rate of the hybraille system and test results for both sequential and simultaneous system over 50 people with 2 samples are disclosed.

In chapter four, the advantages of the proposed work and the reasons of getting these results are discussed. The areas to which the hybraille system can be applied is also included in this part.

CHAPTER TWO

METHODOLOGY

2.1 Hybraille System

In content of this work, a hybraille system is proposed to provide reading and writing capability to visually impaired people to make understanding the environment easy for them. This is a vibrational system and it can be used for both reading and writing operation in an easy and efficient way by the visually impaired people.

The system can convert digital letter to Braille alphabet via its software and vibrates accordingly to provide sensation of corresponding letter to the visually impaired person via this mechanical movement of the electronic into which the system is integrated. The mechanical movement is generated by actuators comprised by the system.

The Linear Resonant Actuator (LRA) and Eccentric Rotary Mass (ERM) are used as an actuating mechanism for the system since they are cheap and it is easy to obtain these components. Additionally, they require less power.

With the helping of these electronic components, easily differentiated vibrational sensations are presented to the visually impaired people. Therefore, they will be able to read the letters accurately via these vibrations. They will be able to write text with the helping of this system since it has special buttons for writing operation. This means that the system may be used as a keyboard by visually impaired people.

The system is integrated into the mechanism of the mouse, keyboard…etc., so it seems like a standard electronic device. With the helping of this property of the system, any negative impact to the visually impaired people from other people will be prevented. Hence, the psychology of the visually impaired people will not be affected by any external factors because of using an additional device which is looking unusual. This approach is preferred to prevent visually impaired people from possible discriminations from other people, caused by using interesting and weird looking devices.

The one embodiment of the system is disclosed in content of this thesis to clearly explain the structure of the electronic device when this system integrated to its body. The mouse, which may be called hybraille mouse, is disclosed and its figures are added for clearly understanding of the system.

The design of the mouse is shown at Figure 2.1 below;

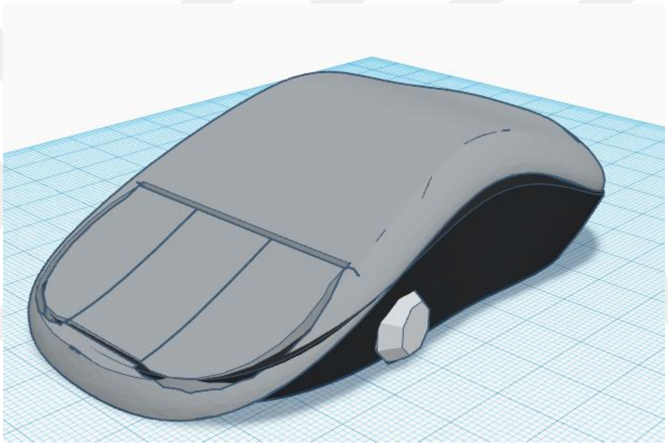


Figure 2.1 Design of the hybraille mouse

Since the hybraille mouse can be used for both reading and writing operation, it has 2 side buttons that are available at right and left side of the mouse to provide transition between write and read operations in an easier way for visually impaired people. The left side button may represent read operation and the right side button may represent write operation or vice versa. The user may press one of these buttons to control the required operation for their task. With the helping of these two buttons, visually impaired people need not to remember which operation was used previously. They may manage the intended task only by pressing the respective button.

In another embodiment of the proposed hybraille mouse system, single button is sufficient to understand which operation was previously selected to continue with the selection of the required operation. The visually impaired people may easily understand which operation was selected previously to continue with the required operation with the helping of this button. Since the button will be in pressed mode when the operation was selected, the visually impaired people may easily understand which operation was selected. They may deactivate if another operation will be selected or it is not needed to be pressed again, if they want to continue with the previously selected operation. The pressed mode of the button may represent read operation and un-pressed mode of the button may represent write operation or vice versa. This button operates like on/off switch for operation selection.

Since the mouse can be used as keyboard by visually impaired people, 6 buttons are available over the mouse. These buttons represent the dots of the Braille cell. It seems that 3 buttons are available over the mouse in Figure 2.1. However, upper and lower parts of these 3 buttons are used for different operations such as representation of different dots of Braille cells. Figure 2.2 shows internal structure of the buttons of the mouse embodiment of the system.

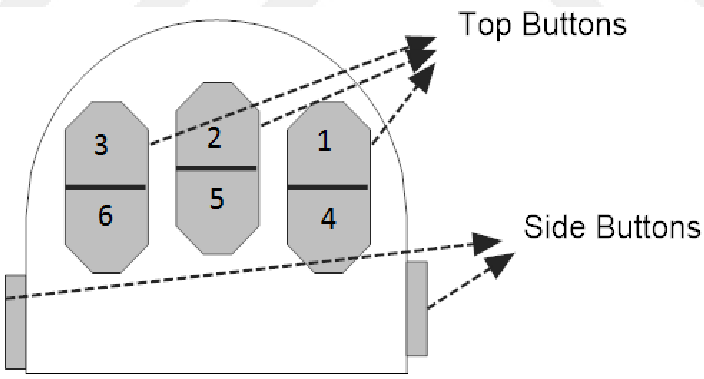


Figure 2.2 Upper and lower buttons of each 3 buttons of hybraille mouse

The visually impaired people press the dots of respective button(s) to write any letter in Braille form. For example, they should press 1, 2, 4 and 5 buttons within a pre-determined time period to write “g” letter since this letter is represented with those numbered buttons as shown in Figure 2.3.

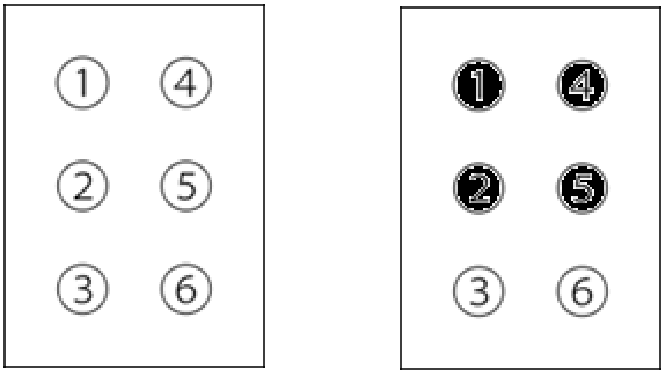


Figure 2.3 Numeration of the buttons of the mouse and representation of "g" letter as braille cell

This property of the mouse will provide keyboard functionality to the hybraille mouse. Therefore, the visually impaired people may use the hybraille mouse instead of using two separate electronic devices while exercising these operations.

2.2 Operation of the Mouse

The hybraille mouse provides vibrational sensation to the visually impaired people to make them extract the letter under its cursor. To discriminate letters from each other, different vibrational sensations should be presented to the visually impaired people in order to prevent misunderstanding of any letter.

In prior art technologies, the Braille cells are displayed to the user with the helping of actuators or electrodes (Maham et al., 2016).

The proposed system also uses actuators to present the letters to the user, however the working operation of the actuators are different in this system. In this system, the actuators are used to generate vibration signal corresponding to the letter which is intended to be read by the visually impaired people.

The operation of the mouse is based on vibrational sense presented to the user. To discriminate the letters from each other, different vibration signals should be generated. The English alphabet is referred to explain working mechanism of the mouse. 26 letters exist at English alphabet as shown in Figure 2.4. Therefore, anyone may think that at least 26 different vibration signals are needed to discriminate these letters from each other while presenting them to the visually impaired people.

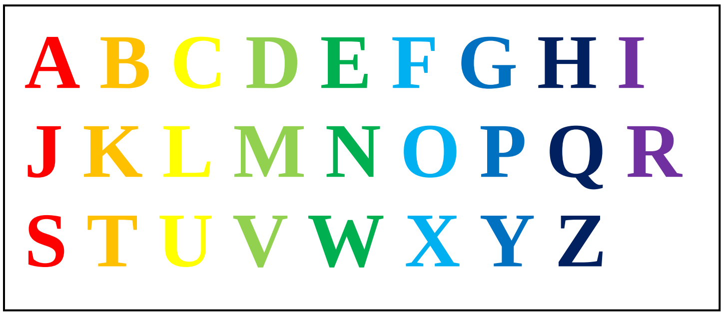


Figure 2.4 English alphabet

However, it would be difficult for the visually impaired people to remember these 26 different vibration signals to extract each letter. Therefore, the proposed work is aimed to develop less complex vibrational system for the visually impaired people. Hence, they will read the letter with less number of vibration signals and they do not need to remember higher number of different vibration signals with the helping of proposed work. The proposed work will be easier but more efficient solution to provide them observation of digital information with higher accuracy.

To extract how many different vibration signals are needed for the realisation of this system, the Braille cell structure is thought. As shown in Figure 1.23 and Figure 2.3, the Braille cell has 6 dots which are placed at 3 rows and 2 columns. This means that 64 different characters may be represented with the helping of this Braille cell.

To make simpler mechanism for the system of the mouse, each column of the Braille cells is taken into consideration separately. Since 3 dots are taken into consideration with this approach, at least 2^3 different vibration signals are required to represent each column of the Braille cell. Therefore, each Braille cell will be represented with the combination of 2 vibration signals since it has 2 columns.

Table 2.1 Signal representations of the braille dots for each column

Signal Number	Corresponding Dots
Signal 1	○○○
Signal 2	○○●
Signal 3	○●○
Signal 4	○●●
Signal 5	●○○
Signal 6	●○●
Signal 7	●●○
Signal 8	●●●
Signal 9	End of Character

As shown in Table 2.1, end of the character signal is also needed in order to prevent confusion of sequentially presented letters. This signal means that present letter is presented to the visually impaired people and the mouse will start to present next letter to them. After two sequential vibration signals, end of the character signal is generated to accurately understanding of the two sequentially presented letters without any confusion.

To explain how the mouse vibrates corresponding to the presented letter, please find below Figure 2.5 which represents "a" letter with vibration signals.

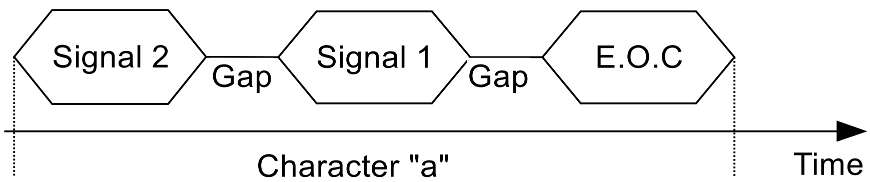


Figure 2.5 Representation of "a" letter with vibration signals

In Figure 1.24, representation of "a" letter in Braille alphabet is shown. By looking the Table 2.1 to remember signal representation of the Braille dots, it can be extracted that "a" letter can be represented with the combination of Signal 2 and Signal 1 sequentially. End of the character signal is generated in order to provide understanding to the visually impaired people to recognise that the one of the read character is finished. A gap exists between each of the two sequential vibration signals since each of them can be clearly understood by the visually impaired people without interference between any of two of the vibration signals.

Each letter can be read in this manner if all the signals are learnt before starting to use the system since all of the generated vibration signals are different from each other.

2.3 Vibration Mechanism

The vibration signals are generated with the helping of the actuators. Linear Resonant Actuator (LRA) and Eccentric Rotary Mass (ERM) are selected for actuating mechanism of the system since their advantageous properties such as being cheap, easily obtainable, less power requirement, easy to be driven, high vibration strength…etc.

DRV2625 EVM-CT haptic evaluation kit is selected for the proposed work since it comprises LRA and ERM actuators, DRV2625 driver which is used for driving ERM and LRA actuators, capacitive touch buttons which are intended to be used as mouse buttons, MSP430 microcontroller to program the system, Bluetooth module to provide communication between external devices…etc. integrated to it. The kit is powered by connecting to the USB port of the computer via micro-USB cable. It has memory to record generated haptic effects via software. Figure 2.6 shows the existing components at the kit (Texas Instruments, 2017).

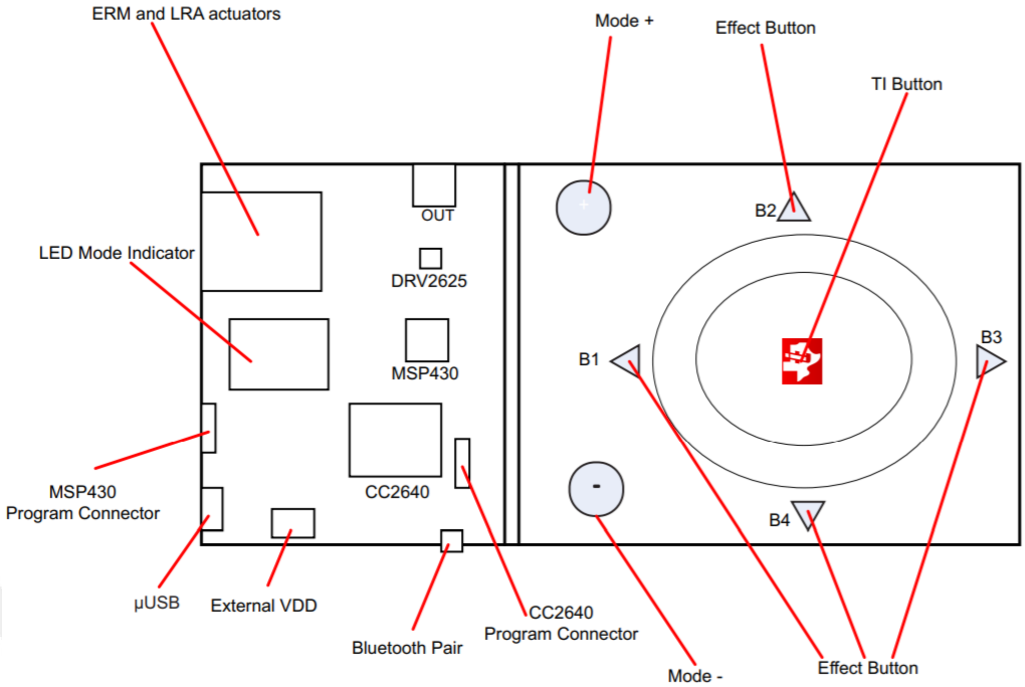


Figure 2.6 Board diagram of DRV2625 EVM-CT kit

This single kit helps us to simulate the hybraille mouse without using any additional electronic component.

The kit comprises 7 capacitive touch buttons. They are used to simulate the buttons of the proposed mouse. For example, Mode +, Mode -, B1, B2, B4 and TI button, which is located at the centre of the capacitive ring, are used to simulate six buttons on the mouse for Braille cell writing operation. Additionally, B3 button is used to simulate transition button of the mouse which is used for transition between reading and writing operations. Therefore, the kit comprises all the features to simulate the proposed hybraille mouse. The DRV2625 EVM-CT kit is shown in Figure 2.7 (Texas Instruments, 2017).

Figure 2.7 DRV2625 EVM-CT kit

The LRA actuator can be driven with either sine wave or square wave. However, the ERM actuator can be driven only with square wave. With the helping of drive signals generated by the DRV2625, the different vibration signals can be generated as response.

Since the object of my thesis is the advantageous effect of driving the ERM and LRA actuators sequentially, both sequential system at which ERM and LRA actuators are driven sequentially with a few ms delay and simultaneous system at which ERM and LRA actuators are driven simultaneously are tested. Since the actuators have different properties such as vibration direction, vibration strength…etc., this working principle helps us to generate higher number of different vibration signals which can be easily distinguished from each other. 8 of the vibration signals are kept same at both simultaneous and sequential system to compare the thesis.

2.3.1 Vibration Signals

With the helping of two of the actuators, it is aimed to generate distinguishable vibration signals. Therefore, 8 different vibration signals are generated to present each letter to the user with effects written in Table 2.2.

Table 2.2 Forms of the vibration signals

Signal	ERM	LRA
0	Triple Click	Triple Click
1	Sharp Tick	Sharp Tick
2	Pulsing Sharp	Pulsing Sharp
3	Transition Ramp Down Soft Smooth	Transition Ramp Down Soft Smooth
4	Shoft Bumb	Shoft Bumb
5	Buzz Alert	Buzz Alert
6	Double Click	Double Click
7	Buzz	Buzz

The response vibration signals are directly related to the shape of drive signal of DR2625. In proceeding sub-titles, the form of the vibration signals will be discussed.

2.3.1.1 Triple Click Signal

Signal 0 or 000 dot form of the Braille column is represented with triple click vibration effect. For this representation, both the ERM and LRA is driven with the below signal. The output of the driver is connected to an oscilloscope and this signal is observed at its screen when signal 0 is selected by the user.

It is clear why this signal is named as triple click. Signal 0 is easily discriminated from other signal since it comprises 3 short vibrations as shown in Figure 2.8.

In simultaneous system, the rate of accurately sensation of this signal is 100% as a result of the test over 50 people with 2 samples for each of them. In sequential system, the rate of accurately sensation of this signal is %98, since the test system asks the users which signal it relates without presenting the vibration. The software error occurred while the test process.

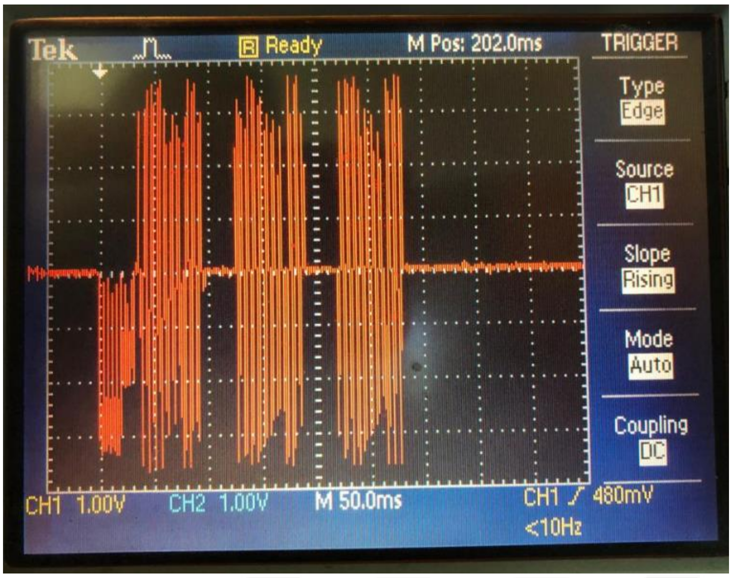


Figure 2.8 Drive signal of triple click vibration effect

2.3.1.2 Sharp Tick Signal

Signal 1 or 001 dot form of the Braille column is represented with sharp tick vibration effect. For this signal form, both ERM and LRA actuators are driven with the signal shown in Figure 2.9.

The drive signal is square even it is not exactly shown in Figure 2.9. Since this signal is unfiltered, the exact waveform is not visible at below figure. The duration this vibration signal is short, so the user can confused about whether this signal is signal 2 or signal 4 in simultaneous system. The rate of accurately sensing these three signals are lowest ones in simultaneous system. In simultaneous system, the rate of accurately sensation of this signal is 56% as a result of the test run over 50 people with 2 samples for each of them.

Since the sensation of the impaired people is higher than normal people, they can easily distinguish these three vibration signals. By the way, after practising the system too much, these three signals are also easily discriminated from each other. The signals can be discriminated by focusing on the sound it produced in addition to their vibration effects.

However, this signal is also easily discriminated from others since both ERM and LRA's vibration can be sensed separately without any vibration interference. Therefore, the users can sensed this signal with 91% accuracy as a result of sequential vibration system test.

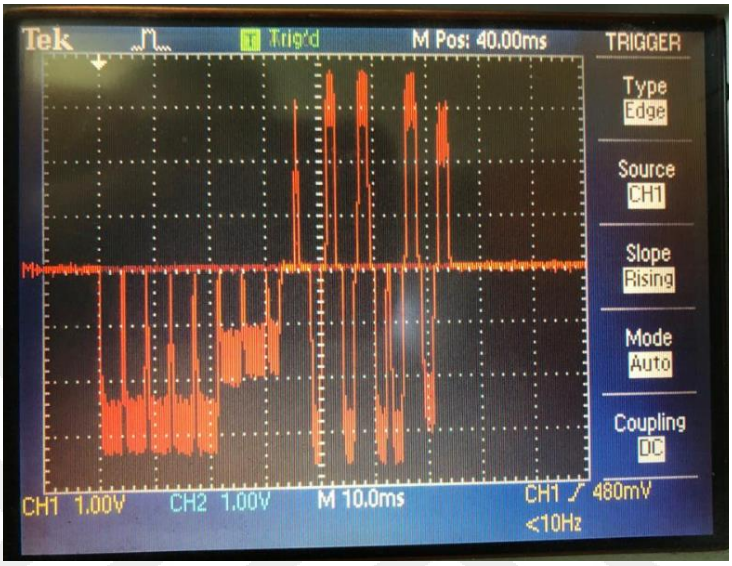


Figure 2.9 Drive signal of sharp tick vibration effect

2.3.1.3 Pulsing Sharp Signal

Signal 2 or 010 dot representation of the Braille column is driven with the signal shown in Figure 2.10. For this vibration effect, both the LRA and ERM actuators are driven with the below signal, but their timings are different depending on the vibration system type. Drive signals are in square form are the on times of the signals are too short to generate pulse effect.

Even the drive signals are different for signal 1 and signal 2, the users generally confused about the effects they sensed since the duration of these two signals are short. However, if the user can focus on both the vibration and the sound it creates when learning period, the signals can be distinguished easier. The rate accurately sensation of this signal is 69% as a result of the simultaneous system test run with 50 people with 2 samples for each of them.

However, the rate of accurately sensation of this signal is 98% in sequential system. Therefore the user can sense the effect generated by each of the actuators separately since no vibration interference occurs.

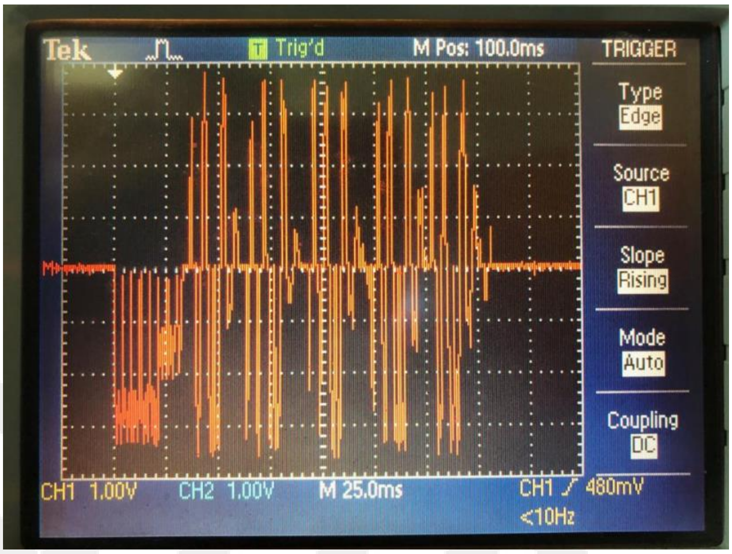


Figure 2.10 Drive signal of pulsing sharp vibration effect

2.3.1.4 Transition Ramp Down Soft Smooth Signal

Signal 3 or 100 dot representation of the Braille column is driven with the signal shown in Figure 2.11. For this vibration effect, both the LRA and ERM actuators are driven with the below signal.

The users sometimes confused about Signal 3 and Signal 7 since their durations are approximately same in simultaneous vibration system. However, the senses they create are distinguishable when focusing on to discriminate them in learning part. For example, signal 3 starts with a strong vibration and getting softer vibration at the end. This is called transition ramp down form. However, signal 7 starts with strong signal and continues in this form until the end of the vibration. In simultaneous system, the rate accurately sensation of this signal is 78% as a result of the test run with 50 people with 2 samples for each of them.

The accuracy of sensing this signal is 95% in sequential system. The user can easily discriminate this signal from signal 7. Since their initials parts are different from each other. Signal 3 generates short vibration effect at its beginning. However signal 7 generates strong and long vibration effect. Hence the users easily differentiate these signals at learning period of the test system.

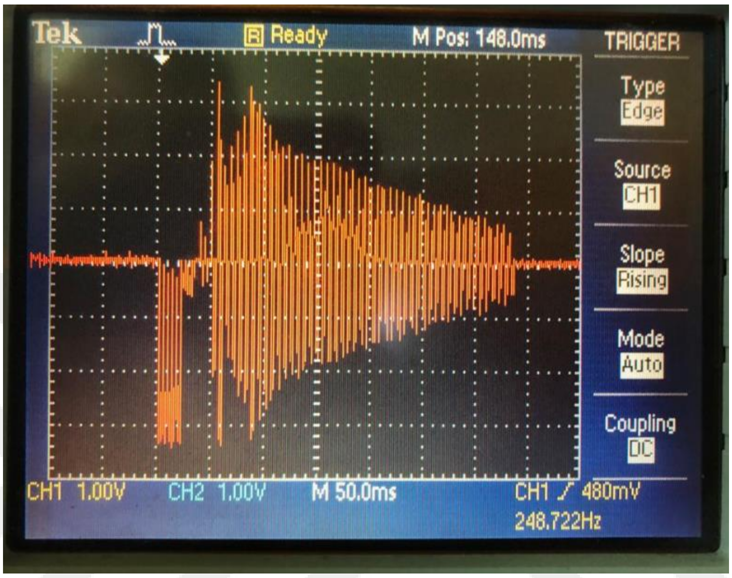


Figure 2.11 Drive signal of transition ramp down soft smooth vibration effect

2.3.1.5 Soft Bumb Signal

Signal 4 or 100 dot representation of the Braille column is driven with the signal shown in Figure 2.12. For this vibration effect, both the LRA and ERM actuators are driven with the below signal.

Even the drive signals are different for signal 1 and signal 2, the users generally confused about the effects they sensed since the duration of these two signals are short in simultaneous system test. However, if the user can focus on both the vibration and the sound it creates when learning period, the signals can be distinguished easier. The rate accurately sensation of this signal is 65% as a result of the test run with 50 people with 2 samples for each of them for simultaneous vibration system.

However, the accuracy rate of this signal is 88% as a result of test run for sequential system. Since the users sensed the vibration of ERM and LRA separately and without any vibration interference, the accuracy rate of sequential system is higher than simultaneous system.

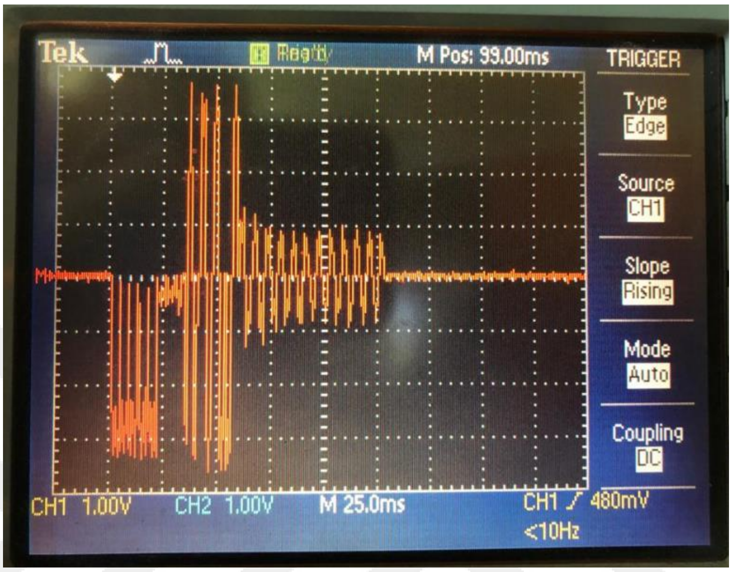


Figure 2.12 Drive signal of soft bumb vibration effect

2.3.1.6 Buzz Alert Signal

Signal 5 or 101 dot representation of the Braille column is driven with the signal shown in Figure 2.13. For this vibration effect, both the LRA and ERM actuators are driven with the below signal.

This signal has the higher rate of accurately sensing by the user since its vibration duration is too long. This is approximately long version of signal 7 in simultaneous vibration system. The drive signal of signal 5 is continuous long vibration effects. In simultaneous vibration system, the rate of accurately sensation of this signal is 100% as a result of the test run with 50 people with 2 samples for each of them.

By the way, the accuracy of sensation of this signal is 98% at sequential system since an error occurred at software. The test asked the user to select the button which the vibration relates to without presenting vibration to the user. However, the accuracy of sensation of this signal is still high at sequential system.

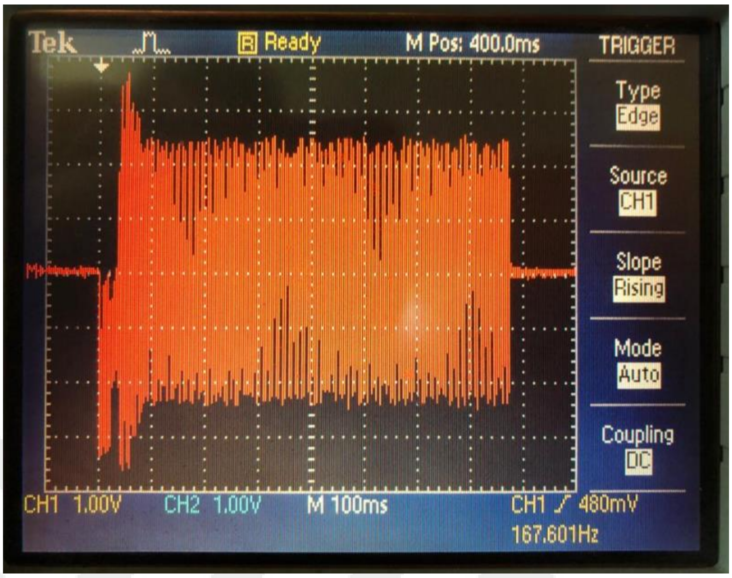


Figure 2.13 Drive signal of buzz alert vibration effect

2.3.1.7 Double Click Signal

Signal 6 or 110 dot representation of the Braille column is driven with below signal as shown in Figure 2.14. For this representation both the ERM and LRA is driven with this signal.

It can be easily observed this may be double click version of signal 0 and signal 6 is also one easily distinguishable signal since its effect is accurately sensed by the users. In simultaneous system the rate of accurately sensation of this signal is 94% as a result of the test run with 50 people with 2 samples for each of them.

By the way, the accuracy rate of this signal is 98% in sequential system. This signal is the one which can be easily distinguishable by the users at both of the system.

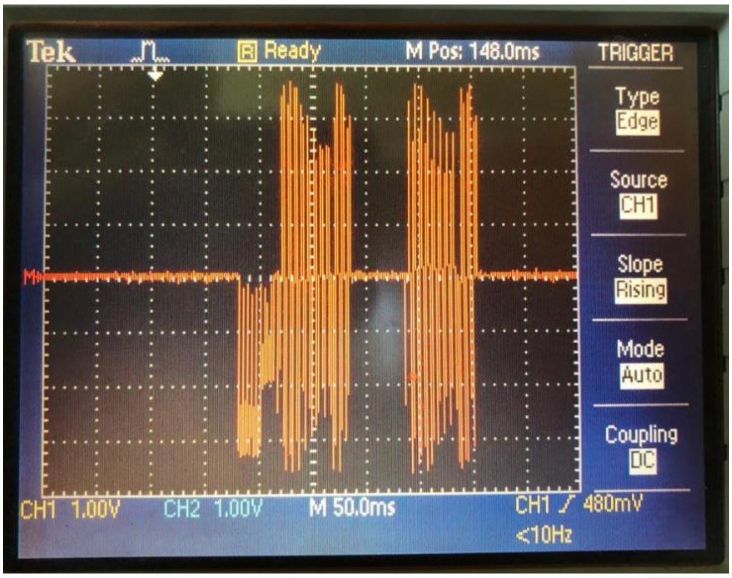


Figure 2.14 Drive signal of double click signal

2.3.1.8 Buzz Signal

Signal 7 or 111 dot representation of the Braille column is driven by the below signal shown in Figure 2.15. To generate signal 7, both the ERM and LRA actuators are driven with this signal.

This signal is approximately the shortest version of the signal 5 corresponding to the simultaneous system, hence it can be easily distinguished from this signal. However, the users are generally confused between signal 7 and signal 3 while selecting the represented button of their sensation. Their duration are nearly same, however the signal 3 has strong vibration at the beginning and getting softer at the end, but signal 7 has long constant vibration effect. In simultaneous system, the rate accurately sensation of this signal is 86% as a result of the test run with 50 people with 2 samples for each of them.

However, the signal has highest accuracy rate 100% as a result of test for sequential system. The user can distinguish this signal since their initial parts are different.

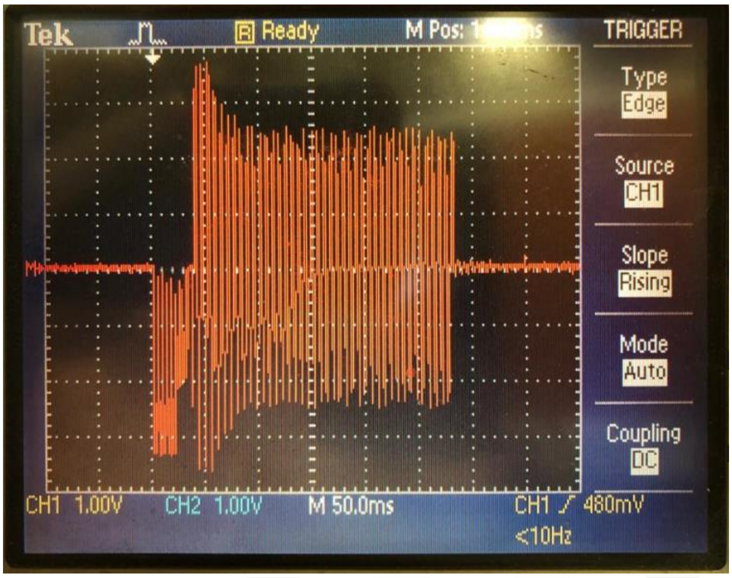


Figure 2.15 Drive signal of buzz vibration effect

CHAPTER THREE

RESULTS

To observe the efficiency of the hybraille system for both reading and writing operation, the test system, which includes learning part and test part, is developed. With the helping of this test system, users can learn the vibration effects in the learning part and test their knowledge in the test part.

The user interface for the writing and reading operations and user interface for test system will be discussed in this part. The accuracy rate of each vibrational effect and average accuracy rate will be disclosed for both sequential and simultaneous system.

3.1 User Interface for Writing and Reading Operations

The user interface (UI) is developed to simulate the operations of the hybraille mouse embodiment of the system. The UI comprises two parts which are selectively activated depending on the selection of operation by the user.

When the impaired people want to write letter(s), the writing operation should be activated with transition button. Then writing part of the UI will be activated and letter(s) will be visible in the write mode output box at UI.

The reading part of the UI comprises 26 box in which respective letters exist. Since this UI is just for simulation of the system, the user should select the box which is intended to be read. When the user selects one of the buttons, he/she will get two sequential vibration signals which represent each of the columns of the Braille cell. Since the vibration signals can be distinguished from each other and the user will learn these signals before using the system, he/she will understand the letter on which the mouse cursor is placed. The writing part of the UI will be deactivated automatically, when the reading operation is selected with transition button by the user.

The UI of for simulation of the reading and writing operations are shown in Figure 2.8.

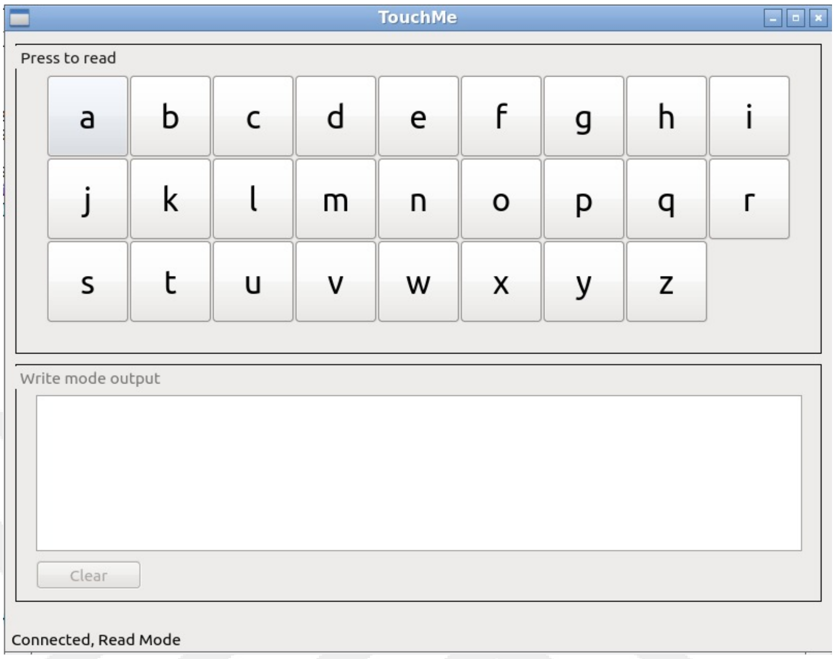


Figure 3.1 User interface (UI) for system simulation

3.2 User Interface and Test Software

The vibration signals should be different and easily discriminated from each other in order to be accurately detected by the visually impaired people. Hence, the rate of accurately sensing these vibration signals is checked via test software.

In content of the software, a User Interface (UI) is created. With the helping of this UI, it is aimed to extract the success rate for sensibility of these different vibration signals. A user name will be asked as a first step. This field is obligatory to record the data for each people separately. After entering the data of user name, the start button should be selected to start the test.

Figure 3.2 UI for user name entry

After selecting start button by the user, learning part of the UI will be shown to the user. The learning part page of UI comprises 8 square buttons which are placed next to each other and in line with each other. Each of these square buttons represents respective vibration signals. Since the user approves to continue with the learning process, this session will be started.

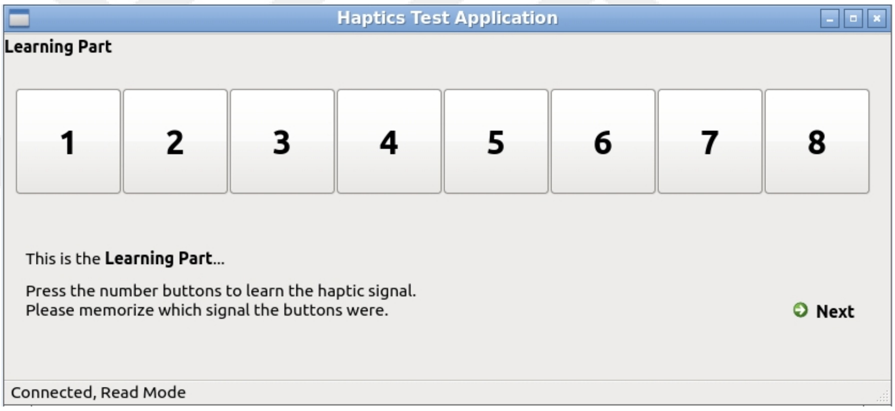


Figure 3.3 Learning part of the UI

In learning process, each vibration signal is presented to the user depending on the user's selection from 8 square buttons. This session continues until the user is sure about that he/she learns the signal and their numeric representation at the square buttons. At the bottom of the page, it is asked to the user whether he/she wants to proceed with test process of the vibration signals. If the user starts to test the sensations of these signals, he/she should select next button to proceed with another session.

The test process helps us to check whether the vibration signals can be discriminated from each other or not. Hence, the rate of sensibility of these signals can be extracted depending on user's feedback for both simultaneous and sequential system.

In test process, different vibration signals are presented to the user randomly and it is expected from the user to select the respective square buttons depending on the presented vibration signals. Each of 8 different vibration signals will be asked to the user two times. Hence, 16 vibration signals are presented to the user in test process. The selection of the user will be recorded each time to corresponding user profile depending on the entered user name. This helps us to review the feedback of the users who tests the system separately.

As a final step, the success rate of the proposed work can be extracted after testing the system with approximately 50 people with 2 samples. We may put some comment on signals why the user generally confused about them and which of them are generally inaccurately selected.

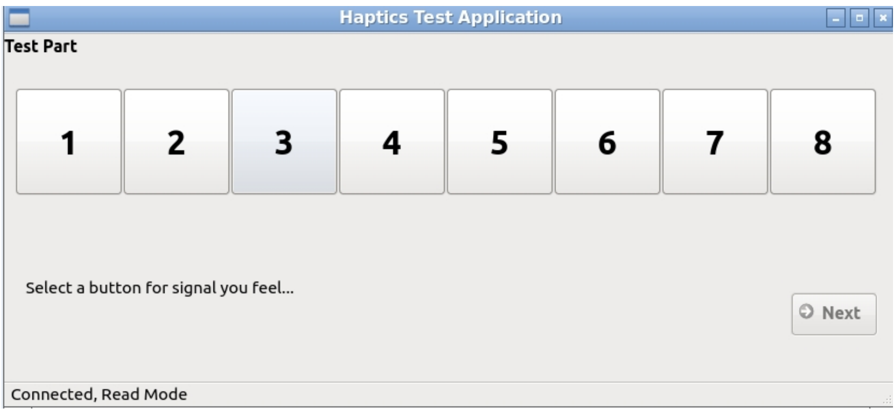


Figure 3.4 UI of test part

The results are recorded below the respective user name. There are 16 cells in form of 8x2 matrixes. Each of the cells represents signal 0 to 7 sequentially. In these cells, user selections are written. For example, if the user select signal 5 instead of signal 0, first cell which represent signal 0 is filled with 5. From the cells, the user feedback can be reviewed and the success rate of each signal can be extracted.

```
Gozde Gunduz Poyraz
0         1         2         3         4         5         6         7
0         1         1         2         4         5         6         7
```

Figure 3.5 An example of test result for a user

The test process is applied to 50 people to get the rate with higher sensitivity. Depending on this test process, the rate for sensing these vibration signals accurately will be extracted for both simultaneous and sequential vibration system. Additionally, it can be extracted which of the vibration signals can be accurately sensed by the user and which of them the user is confused about.

The operation of the system is simple and accuracy is approximately 81% for simultaneous system as a result of the test run over 50 people with 2 samples. The rate of accuracy sensation of each signal with simultaneous system is shown in Table 3.1.

Table 3.1 Accuracy rate of sensation of the signals with simultaneous system

Signal	Accurity Rate (%)
Signal 0	100
Signal 1	56
Signal 2	69
Signal 3	78
Signal 4	65
Signal 5	100
Signal 6	94
Signal 7	86

The operation of the system is simple and accuracy is approximately 97% for simultaneous system as a result of the test run over 50 people with 2 samples. The rate of accuracy of each signal with sequential system is shown in Table 3.2.

Table 3.2 Accuracy rate of sensation of the signals with sequential system

Signal	Accurity Rate (%)
Signal 0	98
Signal 1	91
Signal 2	98
Signal 3	95
Signal 4	88
Signal 5	98
Signal 6	98
Signal 7	100

CHAPTER FOUR
CONCLUSION

In content of the proposed work, a hybraille system is developed to provide reading and writing capability to the impaired people in less complex and advantageous structure over the prior art system. The device operation is based on providing distinguishable vibration signals to present digital information to the user.

The parameters to distinguish the vibration signals are duration, frequency and amplitude of the drive signal, since the actuators respond depending on how they are driven. For example, the signal form may be sinusoidal or square wave, the frequency of the drive signal may be low or high or duration of the drive signal may be short or long. Hence these situations cause some effects on vibration of the actuators. The vibration signal may be sharp or soft, its duration may be long or short…etc.

The system uses LRA and ERM actuators as a vibration mechanism to generate different vibration effects and the basic electronic component of the system is DRV2625 EVM-CT haptic evaluation kit. With the helping of this kit, one of the embodiments of the system, a hybraille mouse, is disclosed in content of this thesis to provide easy understanding of the system.

The system can be integrated into standard electronic device to prevent impaired people from possible discriminations from other people. Therefore, the psychology of the impaired people will not be affected. The system will be ergonomic since it can be integrated into the electronic device such as mouse or keyboard which can be selected by the impaired people.

The system can be portable depending on the integrated electronic device. For example, if it is integrated to the mouse, the mouse can be carried by the user to wherever he/she goes. This is another benefit of the system for its user.

The object of the proposed work is to analyse the difference between simultaneous system in which LRA and ERM operate simultaneously and sequential system in which ERM and LRA operate sequentially. The efficiency of the sequential system is 97% and the efficiency of the simultaneous system is 81%. Hence the efficiency of the sequential system is 16% higher than the simultaneous system since the vibration interference of LRA and ERM motors occur at simultaneous system. The interference of the vibration signals causes inaccurate sensation of different signals since the interference may cause similarity of different vibration signal. Therefore, rate of accurately sensing these signals decreases and the reading performance of this system gets lower than expected even the writing operation performance is same in both systems. The impaired people may come across some difficulties while reading some digital information or get wrong information.

In simultaneous system, the users are confused about the sensations of signal 1, signal 2 and signal 4 and they may select the inaccurate one in test procedure of simultaneous system. However, these signals are easily distinguishable from each other in sequential system as shown in its accuracy table since no vibration interference exists in none of these signals. Hence, the user is aware of which sense related to which signal. The other reason of this higher efficiency is that each symbol is represented approximately two vibration signal and even the user inaccurately senses one of the vibration signals, he/she has another chance from the sequential vibration to extract the character accurately. For example, the initial vibration effects of signal 3 and signal 5 are highly similar, however their last vibration effect are easily distinguishable since signal 3 has longer vibration effect. As another example, the last vibration effects of signal 3 and signal 7 are similar. However the user may easily distinguish these signals depending on their initial vibration effect.

Since the delay between operation of LRA and ERM, the two sequential vibration signals generated by using both of the motors may be thought as signal vibration. Hence, this timing property of sequential vibration signals makes it easy to be learnt and reminded by the user.

This is a successful system with fewer complexes, affordable, portable and any other advantages over prior art system since they are additional device and looking extra-ordinary, difficult to repair, limited screen size…etc.

In our future works, the integration of the system into an electronic will be performed and another alternative will be worked on to developed cheaper version of this system.

The proposed system may be used at different types of electronic devices which is suitable to be integrated for this system. Since the system provides capability of reading and writing any digital information to the impaired people, the device may be used for this purpose by integration to an electronic device which is in suitable form such as keyboard, mouse, mobile phone, tablet…etc. Even the device is not in suitable form for integration, the hybraille system design may be formed in appropriate design.

The device is able to generate different vibrational effects which may be more than 8, each of these effects may be assigned to different messages in electronic device. Therefore, the user may be warned without sound message. This may be useful for the people who are in silent environment such as library, meeting, hospital…etc.

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APPENDICES

Table A.1 Test Results for Simultaneous System

Trials	Signal 1	Signal 2	Signal 3	Signal 4	Signal 5	Signal 6	Signal 7	Signal 8
Trial 1	✓	✓	x	✓	x	✓	✓	✓
	✓	x	x	✓	x	✓	✓	x
Trial 2	✓	x	x	✓	x	✓	✓	✓
	✓	x	x	✓	✓	✓	✓	✓
Trial 3	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	x	x	✓	✓	✓	✓
Trial 4	✓	x	x	✓	✓	✓	✓	✓
	✓	✓	x	✓	✓	✓	✓	✓
Trial 5	✓	x	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	x	✓	✓	✓
Trial 6	✓	x	✓	✓	✓	✓	✓	✓
	✓	x	x	x	x	✓	✓	✓
Trial 7	✓	✓	✓	✓	✓	✓	✓	✓
	✓	x	✓	x	✓	✓	✓	✓
Trial 8	✓	✓	x	✓	✓	✓	x	✓
	✓	✓	✓	✓	x	✓	✓	✓
Trial 9	✓	✓	✓	✓	x	✓	✓	✓
	✓	x	✓	✓	✓	✓	✓	✓
Trial 10	✓	✓	✓	x	x	✓	✓	✓
	✓	x	x	✓	✓	✓	✓	✓
Trial 11	✓	✓	✓	✓	x	✓	✓	✓
	✓	✓	x	✓	x	✓	✓	✓
Trial 12	✓	✓	x	x	x	✓	✓	x
	✓	x	✓	✓	x	✓	✓	x
Trial 13	✓	x	x	✓	x	✓	x	✓
	x	x	✓	x	x	✓	x	x
Trial 14	✓	x	✓	✓	x	✓	x	x
	✓	✓	✓	x	x	✓	✓	x
Trial 15	✓	✓	✓	✓	x	✓	✓	✓
	✓	x	✓	x	✓	✓	✓	x
Trial 16	✓	✓	✓	✓	x	✓	✓	✓
	✓	✓	✓	x	✓	✓	✓	✓
Trial 17	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	x	x	✓	✓	✓
Trial 18	✓	✓	✓	x	✓	✓	✓	✓
	✓	x	x	x	✓	✓	✓	✓
Trial 19	✓	✓	✓	✓	✓	✓	✓	x
	✓	✓	✓	x	✓	✓	✓	✓
Trial 20	✓	✓	✓	✓	✓	✓	✓	✓

Table A.1 Continues

	✓	x	✓	x	x	✓	✓	x
Trial 21	✓	x	✓	✓	x	✓	✓	✓
	✓	✓	✓	x	x	✓	✓	✓
Trial 22	✓	x	x	✓	x	✓	✓	✓
	✓	x	x	x	✓	✓	✓	x
Trial 23	✓	x	✓	✓	✓	✓	✓	✓
	✓	✓	✓	x	x	✓	✓	✓
Trial 24	✓	x	✓	✓	✓	✓	x	✓
	✓	✓	✓	x	x	✓	✓	✓
Trial 25	✓	x	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	x	✓	✓	✓
Trial 26	✓	✓	✓	✓	✓	✓	✓	x
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 27	✓	✓	✓	✓	✓	✓	✓	✓
	✓	x	✓	x	x	✓	✓	✓
Trial 28	✓	x	✓	x	✓	✓	✓	✓
	✓	✓	x	✓	✓	✓	✓	✓
Trial 29	✓	✓	✓	✓	✓	✓	✓	✓
	✓	x	✓	✓	✓	✓	✓	✓
Trial 30	✓	x	✓	x	✓	✓	✓	✓
	✓	✓	x	✓	✓	✓	✓	✓
Trial 31	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	x	✓	✓	✓
Trial 32	✓	x	✓	✓	x	✓	✓	✓
	✓	x	✓	✓	✓	✓	✓	✓
Trial 33	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	x	✓	✓	✓	✓	✓
Trial 34	✓	x	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 35	✓	x	x	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 36	✓	✓	✓	✓	x	✓	✓	✓
	✓	x	x	✓	✓	✓	✓	✓
Trial 37	✓	x	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	x	✓	✓	✓
Trial 38	✓	✓	x	✓	x	✓	✓	✓
	✓	✓	x	✓	✓	✓	✓	✓
Trial 39	✓	✓	✓	✓	✓	✓	✓	x
	✓	x	x	✓	✓	✓	✓	✓
Trial 40	✓	x	x	✓	x	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 41	✓	✓	✓	✓	x	✓	✓	✓
	✓	x	x	✓	✓	✓	✓	✓
Trial 42	✓	✓	✓	✓	✓	✓	✓	✓

Table A.1 Continues

	✓	✓	x	✓	✓	✓	✓	✓
Trial 43	✓	✓	✓	✓	✓	✓	✓	x
	✓	x	✓	✓	x	✓	✓	✓
Trial 44	✓	x	✓	✓	✓	✓	✓	✓
	✓	x	x	✓	✓	✓	✓	✓
Trial 45	✓	x	✓	✓	✓	✓	✓	✓
	✓	x	✓	x	✓	✓	✓	✓
Trial 46	✓	✓	✓	✓	✓	✓	✓	✓
	✓	x	✓	✓	✓	✓	✓	✓
Trial 47	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 48	✓	✓	✓	✓	✓	✓	✓	x
	✓	x	x	✓	✓	✓	✓	✓
Trial 49	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	x	x	✓	✓	✓	✓
Trial 50	✓	✓	✓	✓	✓	✓	✓	✓
	✓	x	✓	✓	✓	✓	✓	✓

Table A.2 Test Results for Sequential System

Trials	Signal 1	Signal 2	Signal 3	Signal 4	Signal 5	Signal 6	Signal 7	Signal 8
Trial 1	✓	✓	✓	x	✓	✓	✓	✓
	✓	✓	✓	x	✓	✓	x	✓
Trial 2	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	x	✓	✓	✓
Trial 3	✓	✓	x	✓	x	✓	✓	✓
	✓	✓	✓	✓	x	✓	✓	✓
Trial 4	✓	✓	✓	✓	x	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 5	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 6	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 7	✓	✓	✓	✓	x	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 8	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	x	✓	✓	✓	✓
Trial 9	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 10	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 11	✓	✓	✓	x	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 12	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 13	✓	✓	✓	✓	x	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 14	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 15	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 16	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 17	✓	✓	✓	x	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 18	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 19	✓	x	✓	✓	x	✓	✓	X
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 20	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	x	✓	✓	✓
Trial 21	✓	✓	✓	✓	✓	✓	✓	✓

Table A.2 Continues

	✓	✓	✓	✓	✓	✓	✓	✓
Trial 22	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 23	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	x	✓	✓	✓	✓	✓
Trial 24	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 25	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 26	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 27	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 28	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 29	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 30	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 31	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	x	✓	✓
Trial 32	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 33	✓	x	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 34	✓	✓	✓	✓	✓	✓	✓	✓
	✓	x	✓	✓	✓	✓	✓	✓
Trial 35	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	x	✓	x	✓
Trial 36	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 37	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 38	✓	✓	✓	✓	✓	✓	✓	✓
	✓	x	✓	✓	✓	✓	✓	✓
Trial 39	✓	x	✓	✓	✓	✓	✓	✓
	✓	x	✓	✓	✓	✓	✓	✓
Trial 40	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 41	✓	✓	✓	✓	✓	x	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 42	✓	✓	✓	✓	✓	✓	✓	✓
	✓	x	✓	✓	✓	✓	✓	✓
Trial 43	✓	✓	✓	✓	✓	✓	✓	✓

Table A.2 Continues

	✓	✓	✓	✓	✓	✓	✓	✓
Trial 44	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 45	✓	✓	✓	✓	✓	✓	✓	✓
	✓	x	✓	✓	x	✓	✓	✓
Trial 46	✓	x	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	x	✓	✓	✓
Trial 47	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 48	✓	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 49	x	✓	✓	✓	✓	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓
Trial 50	✓	✓	✓	✓	x	✓	✓	✓
	✓	✓	✓	✓	✓	✓	✓	✓