ACIBADEM MEHMET ALI AYDINLAR UNIVERSITY
INSTITUTE OF HEALTH SCIENCES

TOUCH VISION: TACTILE-VISION SENSORY SUBSTITUTION DEVICE

SELCEN NECİBE GÖKDUMAN

M.Sc. THESIS

DEPARTMENT OF MEDICAL BIOTECHHNOLOGY

SUPERVISOR
Prof. Tanıl Kocagöz

ISTANBUL-2024

ACIBADEM MEHMET ALI AYDINLAR UNIVERSITY
INSTITUTE OF HEALTH SCIENCES

TOUCH VISION: TACTILE-VISION SENSORY SUBSTITUTION DEVICE

SELCEN NECİBE GÖKDUMAN

M.Sc. THESIS

DEPARTMENT OF MEDICAL BIOTECHHNOLOGY

SUPERVISOR
Prof. Tanıl Kocagöz

ISTANBUL-2024

Department:	Medical Biotechnology
Program:	Medical Biotechnology
Thesis Title:	Touch Vision
Student's name and Surname:	Selcen Necibe Gokduman
Date of Defence:	01/02/2024

This is to certify that I have examined this copy of master thesis. I have found that she prepared after fulfilling the specified requirements in the associated legislations before the final examining committee whose signatures are below.

Jury Member (Head of the Defense)	Prof. Tanıl Kocagöz Institute of Health Sciences	Signature
Jury Member (Thesis Supervisor)	Asst. Prof. Ceyhun Ekrem Kırımlı Faculty of Engineering and Natural Sciences	Signature
Jury Member	Assoc. Prof. Burak Aksu School of Medicine	Signature

DECLARATION

I declare that this thesis work is my own work, I had no unethical behavior at any stages from the planning to the writing of the thesis, I obtained all the information in this thesis in accordance with academic and ethicel rules, I cited all the information and comments that were not obtained with this thesis work, and I provided resources in the list of references. I also declare that there was no violation of any patents and copyrights during the study and writing of this thesis.

Date 05.01.24

Selcen Necibe Gokduman

(Signature)

PREFACE AND ACKNOWLEDGEMENT

First and foremost, words would be insufficient to express my gratitude to my dear advisor Prof. Tanıl Kocagöz. I truly appreciate His constant support and valuable guidance throughout my master. I am grateful for the opportunities that He provided for my growth as a scientist. Without all of it, it would be difficult for me to complete this challenging journey.

I would like to thank Lect. PhD Seda Nilgün Dumlu for her knowledge and guidance during my study. I am really grateful for Her support and mentorship. Also, I would like to than Asst. Prof. Ceyhun Ekrem Kırımlı for His valuable guidance in this study.

I embarked on a different journey when I decided to begin Medical Biotechnology Master's Program. Sometimes, it was more than challenging to continue this process with enthusiasm. When it gets difficult, I returned my loved ones for their endless love and support. I appreciate the unwavering support that my dear brother Halil Gökduman provided me during my study. His presence was a safe space for me to recharge during challenging times. The support and love of my grandparents, Bayram Gökduman and Aliye Gökduman was mean a lot to me. I would like to thank my parents for their support along the way.

I would also like to thank my dearest close friends for their heartfelt presence, all the support and love they gave me; Betül Güran, Sena Ayhün, Beyza Tekin, Erva Metin, Havva Demirkaya, and Beyza Kalenderoğlu.,

I would like to express my gratitude to my friends in Arge Team for their joyful support for my thesis defense, this will remain a core memory for me. I am grateful for the laughter that we shared with.

TABLE OF CONTENTS

DECLARATION iii

PREFACE AND ACKNOWLEDGEMENT iv

TABLE OF CONTENTS v

LIST OF FIGURES vii

LIST OF TABLES ix

LIST OF ABBREVIATIONS AND SYMBOLS x

ÖZET 1

ABSTRACT 2

1 INTRODUCTION AND AIM 3

2 BACKGROUND 5

2.1 Literature Review 5

2.2 Sensory Substitution Devices 8

2.2.1 Components of sensory substitution devices 13

3 MATERIALS AND METHODS 16

3.1 Materials 16

3.2 Methods 17

3.2.1 Circuit design and simulation 17

3.2.1.1 Actuator types 18

3.2.1.2 Determining the number of motors 18

3.2.1.2.1 Average size of forehead area in human body 18

3.2.1.2.2 Two-point discrimination distance on the forehead 19

3.2.1.2.3 Designing the test circuits 20

3.2.2 Circuit fabrication 22

3.2.3 Electronic characterization of the integrated system 23

3.2.4 Software design 23

4 RESULTS 30

4.1 Circuit Fabrication 30

4.2 Acquired Images 31
4.2.1 Demonstration of the image processing software 31
4.2.2 Application of filtering techniques 36
4.2.2.1 Thresholding of Frame 1 36
4.2.2.2 Thresholding of Frame 2 41
4.2.2.3 Thresholding of Frame 3 46
5 DISCUSSION 51
5.1 Circuit Fabrication - Motor Matrix 51
5.2 Image Processing 51
5.2.1 Discussion of The Resulted Acquired Images 51
5.2.2 Discussion of The Filtering Techniques Applied to Gray-Scale Images.. 52
5.3 Suggested Modifications and Improvement of Touch Vision 54
6 CONCLUSION 55
7 REFERENCES 56
8 CURRICULUM VITAE 62

LIST OF FIGURES

Figure 1. WeWalk Walking Stick 7

Figure 2. Tactile Visual Sensory Substitution Device Developed by Bach-y-Rita and C.Collins 9

Figure 3. Tactile-vision substitution device 10

Figure 4. Indoor navigation guide 11

Figure 5. Main components of a sensory substitution device system 13

Figure 6. Schematic of designed test circuit 21

Figure 7. The designed vibration motor matrix 21

Figure 8. The motor matrix 22

Figure 9. The rear components of the printed motor circuit 22

Figure 10. Image Processing Algorithm 24

Figure 11. The image processing code (part 1) 29

Figure 12. The image processing code (part 2) 29

Figure 13. Printed LED test circuit 30

Figure 14. The motor matrix produced 30

Figure 15. The rear components of the printed motor circuit produced 31

Figure 16. Original Frame 1 (color image) 33

Figure 17. Gray-scale image of Frame 1 33

Figure 18. Resized gray-level image of Frame 1 33

Figure 19. Original Frame 2 (color image) 34

Figure 20. Gray-scale image of Frame 2 34

Figure 21. Resized gray-level image of Frame 2 34

Figure 22. Original Frame 3 (color image) 35

Figure 23. Gray-scale image of Frame 3 35

Figure 24. Resized gray-level image of Frame 3 35

Figure 25. Adaptive thresholding of gray-scale Frame 1 36

Figure 26. Resized image of Figure 25 36

Figure 27. Gaussian thresholding of gray-scale Frame 1 37

Figure 28. Resized image of Figure 27 37
Figure 29. Adaptive-Gaussian thresholding of gray-scale Frame 1 38
Figure 30. Resized image of Figure 29 38
Figure 31. Otsu’s thresholding of gray-scale Frame 1 39
Figure 32. Resized image of Figure 31 39
Figure 33. Multi-Otsu thresholding of Frame 1 40
Figure 34. Resized image of Figure 33 40
Figure 35. Adaptive thresholding of gray-scale Frame 2 41
Figure 36. Resized image of Figure 35 41
Figure 37. Gaussian thresholding of gray-scale Frame 2 42
Figure 38. Resized image of Figure 37 42
Figure 39. Adaptive-Gaussian thresholding of gray-scale Frame 2 43
Figure 40. Resized image of Figure 39 43
Figure 41. Otsu’s thresholding of gray-scale Frame 2 44
Figure 42. Resized image of Figure 41 44
Figure 43. Multi-Otsu thresholding of Frame 2 45
Figure 44. Resized image of Figure 43 45
Figure 45. Adaptive thresholding of gray-scale Frame 3 46
Figure 46. Resized image of Figure 45 46
Figure 47. Gaussian thresholding of gray-scale Frame 3 47
Figure 48. Resized image of Figure 47 47
Figure 49. Adaptive-Gaussian thresholding of gray-scale Frame 3 48
Figure 50. Resized image of Figure 49 48
Figure 51. Otsu’s thresholding of gray-scale Frame 3 49
Figure 52. Resized image of Figure 51 49
Figure 53. Multi-Otsu thresholding of Frame 3 50
Figure 54. Resized image of Figure 53 50

LIST OF TABLES

Table 1. Machines and Equipments 16
Table 2. Consumables 17
Table 3. The distance at which forehead receptors can distinguish between two mechanical factors 20

LIST OF ABBREVIATIONS AND SYMBOLS

BGR	Blue-Green-Red
DC	Direct Current
ERM	Eccentric Rotating Mass
LED	Light Emitting Diode
ms	milliseconds
OpenCV	Open-Source Computer Vision Library
PCB	Printed Circuit Board
PWM	Pulse Width Modulation
RP	Raspberry Pi
SSD	Sensory Substitution Device

ÖZET

Dokunsal Görme: Dokunsal-Görme Duyusal Yerleştirme Cihazı

Sunulan projenin ana amacı, görme engelli kimselerin bağımsız ve güvenli bir şekilde hareket edebilmesini sağlayacak giyilebilir rehber bir dokunsal-görme entegre sistemi geliştirilmesi olarak özetlenebilir. Eksik olan görme yetisini, başka bir duyu aracılığıyla görme engelli kimseye iletmeyi sağlayan sistem ve aygıtlara da "Duyusal Yerine Koyma Aygıtları" adı verilmektedir. Bu sistem ve aygıtlar, başka bir duyusal organ tarafından toplanan bilgiyi alır, işler ve kullanıcıya onun algılayabileceği şekilde aktarır [2, 3, 4, 5]. Yukarıda bahsedilen hedeflere ulaşmak için bu çalışmada duyu yerleştirmesinin alın bölgesi ile kullanıcıya sağlanması uygun görülmüştür. Bu çalışmanın temel amacı, görme engelli kullanıcıları bulundukları ortamdaki parlaklığa göre yönlendirmektir. Önerilen entegre dokunsal görme duyu yerleştirme sistemini geliştirmek için görüntü işleme ve dokunsal titreşim üretme yöntemleri kullanılmıştır. Özetlemek gerekirse, kullanıcının bulunduğu ortamdan kamera aracılığıyla toplanan görüntüler işlendi ve işlenen görüntüdeki parlaklık değeri bilgisi, titreşim motorları tarafından kullanıcının alnında titreşim oluşturmak için kullanıldı. Kameradan alınan giriş sinyali küçük bir bilgisayarda (Raspberry Pi) saklanır ve işlenir. Elde edilen piksel değerleri görüntü işleme için kullanılmıştır. Daha sonra, görüntünün piksel parlaklık değerleri bir dizi şeklinde elektronik bir karta iletilir ve nicelendirilir. Titreşim motorlarının çalıştırılması için uygun bir görüntü işleme algoritması geliştirilmiştir. Motorların titreşimi, görüntü işleme sırasında ölçülen parlaklık değerlerine göre gerçekleştirilir.

Anahtar Sözcükler: Giyilebilir rehber, Görme engelli, Dokunsal görme duyu yerleştirme, Piksel parlaklık değeri, Görüntü işleme.

ABSTRACT

Touch Vision: Tactile-Vision Sensory Substitution Device

The main purpose of this study was to develop an integrated tactile-vision sensory substitution system (SSDs) which provides wearable assistance for visually impaired people, to navigate through the world, in a safe and independent state. Briefly, SSDs convey the absent sensory information through another functioning sensory organ and achieve this by acquiring the sensory information via a receiver, processing the obtained information and transmitting the processed sensory information through an output component in a way that visually impaired can comprehend [2, 3, 4, 5]. In this study, sensory substitution was generated on the forehead area of the visually impaired user to achieve the goals mentioned above. The main purpose of this study was to navigate visually impaired users according to brightness in their surroundings. Methods of image processing and generating tactile vibration were utilized for developing the proposed integrated tactile vision substitution system. To sum up, the images collected by the camera from the user's environment were processed and brightness value information in the image processed were used to create vibration on the forehead of the user by vibration motors. The input signal acquired from the camera is stored and processed in a small computer (Raspberry Pi). The acquired pixel values were used for image processing. Then, the pixel brightness values of the image are transmitted to an electronic card in the form of an array and quantified. A suitable image processing algorithm was developed for operating the vibration motors. The vibration of the motors is generated according to brightness values quantified during the image processing.

Keywords: Wearable assistance, Visually impaired, Tactile-vision sensory substitution, Pixel brightness value, Image processing

1 INTRODUCTION AND AIM

The ability to see represents the interaction of human beings with their biggest surrounding, the world. The one’s ability to visually perceive and understand the surrounding greatly affects the quality of life. It also plays a crucial role in one’s physical, emotional, and social development. Visual impairments, on the other hand, are commonly observed in human beings. Globally, approximately 295 million people have been reported to have moderate or severe visual impairment [9]. Moreover, it is estimated that around 43 million people have complete vision loss [9].

Over the years, researchers have conducted various studies considering the severity of vision loss. In the light of these studies, various devices have been developed to enhance the quality of life of visually impaired people. White cane and the Braille alphabet are the main tools commonly used by visually impaired people, over the decades. On the other hand, as technology developed, these conventional tools continued to be used in their most basic form. The world has been slowly proceeding for improving the quality of life of visually impaired people, who constitute a large part of the society. Yet, efforts to compensate the lack of technology in this field have also increased in recent years.

In recent years, advanced new solutions for enhancing the life quality of visually impaired people have emerged by utilizing the state of art methods, techniques, and materials. Hence, the development of advanced devices in this field has gained momentum. Various different techniques have been utilized in these studies aimed to improve the quality of life of visually impaired people. The relevant techniques can be listed as follows: sensory substitution [30], sensory enhancement [4,12], spatial orientation and detection of objects [28, 53], and exploration of the environment [35]. The initially utilized technique defines the type of the device that is aimed to be developed. Hence, the primary focus in the development stage of a device for visually impaired is to determine the technique to be employed. The purpose of these studies is to strengthen the connection between visually impaired individuals and the visual world, via guiding/directing them to the desired location by certain stimuli when there are obstacles on the way or dangerous situations are present in the surrounding of the user.

The importance of vision sense may be hard to comprehend if one has already a competent vision. However, vision defects and impairments cause major changes in one's life. Some defects and impairments can be treated yet, most of them are permanent throughout the one's life. Hence, there is a high priority requirement for improving the impaired sense of vision in visually impaired individuals. This study is originated from the idea that requires to act for making a positive impact in the lives of visually impaired people.

2 BACKGROUND

2.1 Literature Review

Visually impaired individuals encounter challenges in various aspects of their daily activities, including reading, education, socialization, and mobility. Hence, visually impaired people often rely on assistive tools for navigating throughout their lives. Thus, assistive technology is required to improve mobility of visually impaired individuals.

Over the course of time, several assistive tools have been developed for visually impaired people to perform their daily activities independently.

White cane is the most commonly used and easily accessible mobility tool for people with a visual impairment. Using a white cane can warn visually impaired people of obstacles on the way, stairs ahead, a nearby sidewalk, and numerous other features in the surroundings that the awareness is needed.

White cane creates vibrations that reaches to the top of the cane, into the user's hand, wrist, and up all the nerves into the brain. Thus, a white cane sends signals to the users in the form of tactile vibration, providing tactile information about the surroundings, thereby allowing these surroundings, especially on the ground, to be explored and obstacles to be detected. Moreover, the users can create mental maps of the surrounding based on the information acquired through moving with a white cane [61]. Although white cane facilitates the orientation of visually impaired users and contributes to their mobility, it has a limited range in detecting objects [62]. Inability in detecting trunk, head-level objects and other over-hanging objects is a major issue of using white cane as an assistive tool [61]. The limits of a white cane lead to inevitable accidents, putting visually impaired in physical danger [62 ,13]. Hence, the safety of assistive tools for visually impaired is significantly important.

With the inception and proliferation of ubiquitous sensing and computational technology, researchers have been able to overcome these limitations by supplementing the basic functionalities of white cane to enable blind people to perform most of these navigation-related activities independently. Researchers have exploited technology in developing technology-based navigational and orientation aids.

Several technology-assisted aids are available to help blind and visually impaired people. The current research uses the state-of-the-art technology to enhance the utility of traditional navigational aids to produce solutions that are more reliable [61].

Most of these aids have exploited white cane as the primary navigation tool and supplemented it with the state-of-the-art technologies for improved immediate tactile information about the ground, drop-offs, direct physical interaction, and signaling effect with surroundings.

In the past decade, a new generation version of the widely used white cane was developed. Basically, the white cane contributes to the ability of visually impaired users to move forward on the road without crashing obstacles. On the other hand, most of the time users may not be able to determine their exact location at the time and they may have to avoid obstacles by trial and error. Minimizing the restrictive properties of the tool used is a key parameter that enables the development of new products. For these reasons, the WeWalk [25, 51] walking stick (Figure 1), which was developed in our country, Turkiye, notifies the user about the obstacles ahead on the road using ultrasonic sensors and provides directions for the determined location if desired. In this way, a white cane with high-tech sensors and software become an equipped tool for visually impaired users. Most importantly, the interaction of visually impaired individuals with the world is became more active and safer.

Figure 1. WeWalk walking stick [25, 51]

Another type of device developed for the visually impaired is invasive brain interfaces [43]. It aims to restore vision disorders and losses with implant devices placed in the brain. Although it is a promising approach, the researchers have not yet fully deciphered the structure and function of the brain. On the other hand, it is required to develop safer methods and devices for placing the implants into the brain. There may be severe drawbacks; nerves in the brain may be damaged during device insertion or infection may occur after the insertion is completed. Given these shortcomings, brain implants can have serious consequences. As a result, advanced knowledge and techniques that are not currently available are required for a successful brain implantation.

One of the device development methods for the visually impaired is the substitution of non-visual sensory information [22]. Devices that enable to transmit the visual data to a visually impaired person through another sense are called "Sensory Substitution Devices" (SSDs). Sensory substitution devices acquire the related data, process the information collected and transmit it to the user through another sensory organ [2, 22, 34, 45]. Different types of sensory information can be utilized with these devices. In general, sensory substitution devices are named after other sensory information/organ that they use to replace missing sensory information. For example, if the missing visual sensory information is transferred to the disabled person via the auditory sense organ, it is called an "auditory sensory replacement device".

2.2 Sensory Substitution Devices

SSDs developed so far are devices that convey the deficient visual information to a visually impaired person through tactile or auditory senses. These have been called auditory-vision sensory substitution device or tactile-vision substitution device. Moreover, it was shown that the substituting signals evoke an increased activity in the occipital cortex after sufficient training with a device that translates visual information into tactile or auditory stimuli [29]. This indicates that the output signal, despite being an auditory or tactile stimulus, is perceived and processed in the same way as a visual stimulus. In this way, the information collected by auditory or tactile sensory substitution devices can be processed and transmitted to people who are visually impaired. Hence, these devices can provide simplified localization, object or shape recognition capabilities for visually impaired users.

In general, auditory-visual sensory substitution devices [1, 38, 52] convert the images taken by the camera into sound and transmit them to the user via headphones. Tactile-vision substitution devices, on the other hand, transform camera signals into tactile stimuli and transmit the information acquired to visually impaired users [22].

Throughout the ongoing studies, the researchers aimed to substitute the sense of vision by using different parts of the human body. One of the earliest tactile-vision substitution devices was developed in 1970s, and this device was named as “Tactile Vision Sensory Substitution (TVSS)” [57]. The image of this device can be seen in Figure 2. This device consisted of a vibrating tactile matrix mounted on the dental chair and a camera connected to it. The images taken from the camera were transmitted by the processors to the vibrating haptic matrix located on the seat. The vibrating touch sensation transmitted to the back area enabled visually impaired users to perceive the image taken with the camera.

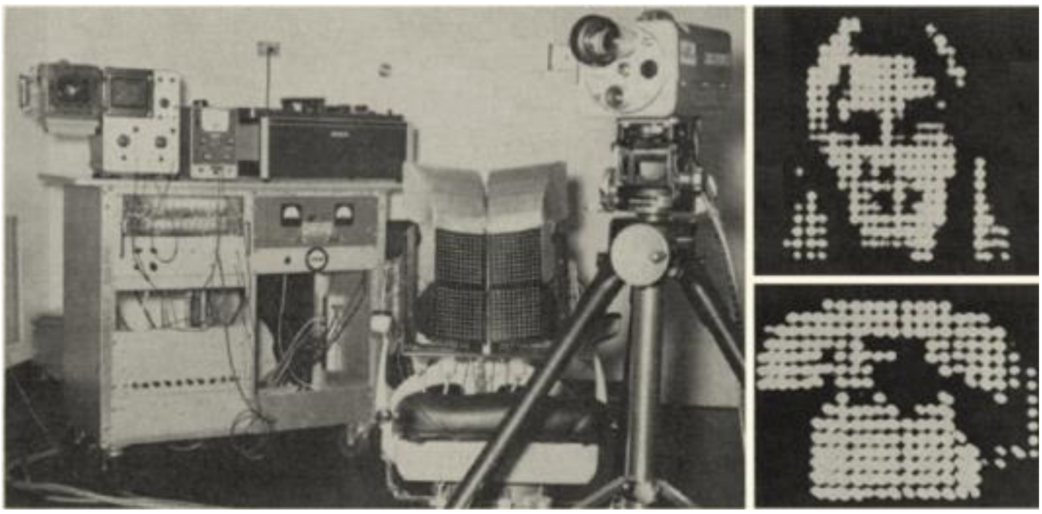

Figure 2. Tactile Visual Sensory Substitution device developed by Bach-y-Rita and C. Collins [16]

To this day, a number of sensory substitution devices have been attempted to be created, but many of them have not been successful in use. Each study differs in terms of the methodology used to transmit the signal and the algorithm it uses to convert this signal. A detailed explanation of how auditory-vision and tactile-vision substitution devices work is given in the following paragraphs by giving examples of these studies.

The device called vOICE [52] can be given as an example of auditory-visual sensory substitution devices. The vOICE consists of a small computer connected to a camera attached to a pair of glasses and converts the collected visual information into an audio signal. The computer algorithm, present in the device, scans each digital image from left to right. Based on the vertical position and brightness of the pixels, the frequency and intensity are determined for each pixel column. A sound associated with the determined frequency and intensity is produced and transmitted to the visually impaired user. High number of bright pixels at the top of a column will translate into a high-frequency sound, while high number of darker pixels will be a quieter, lower-pitched sound. A visually impaired person wearing these glasses would be able to associate different sounds with the visual characteristics of their environment.

Another example of tactile-vision substitution devices is the device named "Forehead Retina System" [31]. This device consists of a camera and electrodes, and the forehead of users was selected as signal transmission area.

As the fundamental method of tactile-vision substitution devices, the images collected with the camera are processed by algorithms in this device and transmitted to the user with the generation of tactile stimulation. Tactile stimulation in this device is generated by electrodes. The signals to be transmitted to the user are converted into a simplified image by using computer vision methods and image processing techniques. The simplified image was generated by first converting the acquired image from the camera into a black-and-white image, and this black-and-white image is transformed into a tactile image and transmitted to the user. The illustrative image of the device and the processed sample image can be seen in Figure 3. The biggest advantage of this device is that it does not occupy an active organ of the user and informs the user about obstacles and objects in the environment.

a. b.

Figure 3. Tactile-vision substitution device: a) Forehead-Retina System, b) The acquired image was converted into a tactile image [31]

In another study in the literature a guide device, similar to the tactile-vision substitution device aimed to be developed in this project, was designed to help visually impaired people to find their way indoors (Figure 4). The device consists of a white cane and an augmented reality device placed on the forehead (Figure 4). This device is named "Indoor NavGuide" [26, 33] is another advanced device developed for visually impaired users (Figure 4). This device enables visually impaired individuals to find their way and direction indoors, and to move forward without hitting any obstacles. The device achieves these functions by capturing visual information from the surrounding through the use of a camera, using computer vision algorithms, accessing structural information of buildings via floor diagrams, and providing an option for requesting assistance from a web-connected group of volunteers. Besides, this device can provide tactile stimulation to users via vibration motors placed on the forehead. The distinguishing feature of this device is that the visually impaired user could reach volunteers in the web network and ask for feedback about the environment. However, an internet connection is required to utilize the distinctive features of the device. This may prevent the use of web dependent features of the device when there is no internet connection or the internet is disconnected.

Figure 4. Indoor navigation guide [26, 33]

Throughout the development of SSDs, various parts of the human body have been used for signal transmission in tactile-vision devices. These parts and organs can be listed as follows; back [16, 57], abdomen [11,36, 47], tongue [10, 29, 57], fingers [6, 20, 30, 32], arm [60], and forehead [31]. The part of the body used for signal transmission determines the efficiency of the sensory substitution. The most important design parameters of sensory substitution devices are the occupation of active sensory organs and how much does this affect user [33]. For instance, which body parts are being occupied by an SSD produced for a visually impaired person? How much of actively used organs or body parts are being occupied by these devices? The answers to these questions determine the eligibility of the SSD. An ideal sensory substitution device is expected not to occupy the user's hands, ears, or other actively used part of the body or the organ.

It was stated that various body parts were used for signal transmission. To evaluate these devices in terms of their eligibility of use, it is known that tactile-vision devices placed on the back and abdomen do not have a convenient use, and signal transmission and resolution are low on this part of the body [7]. Since language is the main communication tool that human beings actively use, the occupancy and constant stimulation of the active organs prevents the device from being ideal. Similarly, the tactile vibration transmitted to the fingers and arm will prevent the user from using their hands and arm without restraint, which is often needed in one’s daily life. In addition to these, since the forehead is not a body part that one actively uses, it is estimated that keeping this area of the body busy for signal transmission would not pose a danger and would provide ease of use. By comparing the availability of the body parts used for tactile-vision substitution, it is aimed to use the forehead region for sensory substitution in this project.

In addition, based on the sensory modalities used for substitution of vision in the SSDs introduced in the previous paragraphs and the examples given, the utility of each type of SSDs is discussed. Auditory instructions given by auditory-vision substitution devices may prevent users from perceiving sounds that act as cues for dangerous situations or that give clues about their spatial orientation. At the same time, tactile-vision devices are considered to be safer than auditory-vision replacement devices [5, 21]. The tactile-vision sensory substitution device shown in Figure 3 does not occupy an actively used body part and while this is a convenient feature, transmission of the tactile stimulation is achieved via electrodes and this prevents long-term use of the device. The efficiency of the electro-tactile stimulation generated by the electrodes could be negatively affected due to heat generation and bodily secretions such as sweat. The integration of mechanical components instead of electrodes may increase the efficiency of stimulation of the device to provide an adequate sensory transmission for a long period of time. In conclusion, in this project, it is aimed to transmit the tactile signal onto the forehead of users with haptic actuators.

2.2.1 Components of sensory substitution devices

Sensory substitution devices generally consist of four components: (1) the input device that collects the information aimed to be conveyed, (2) the processing unit that converts the obtained information by following the created algorithm, (3) the driver circuit and (4) an output device that transmits the converted information to the user. A sensor is used as an input device, a processor as a converter, a driver to transmit the signal and power required for the actuators to work, and actuators as an output device [39, 40]. An illustration of the relation between these main components is shown in Figure 5.

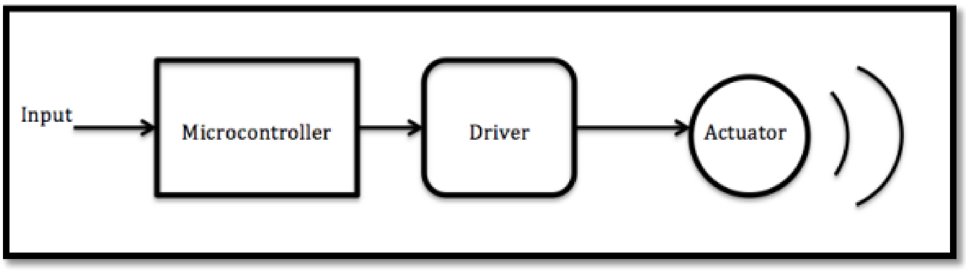

Figure 5. Main components of a sensory substitution device system [23]

Additionally, due to the artificial nature of the components used in SSDs, human-computer interfaces are utilized to transform the sensory information obtained into a sense that can be perceived by humans. An important part of the technological concept of sensory substitution devices are the sensory matrices responsible for stimulation. In general, the information desired to be conveyed to the users is provided by tactile, auditory, or visual matrices [40]. It is aimed to develop the sensory matrix to be used in this project by using the sense of touch, hence a tactile stimulation is planned to be generated.

Thanks to the advance technology, the matrices used today are components that have small dimensions, low energy consumption and generally low cost. Sensory substitution matrices can consist of mechanical and electronic components. Electrodes as electrotactile component [31]; for mechanical actuator stimulation, linear vibration motor (LRA) [18, 3, 59], eccentric rotation motor (ERM) [3, 48, 59] and piezoelectric transducers [3, 37, 59] are being using. In addition to these, there are studies to generate tactile stimulation with ultrasound waves [3]. Depending on the type of actuators, various stimulation methods emerge; the most common of these methods can be listed as mechanical deformation, vibratory-tactile-stimulation (vibrotactile stimulation), and electrotactile stimulation.

Vibration components such as LRA (Linear Resonant Actuator) or ERM (Eccentric Rotating Mass) can be used through control software. Vibrating components are being utilized to express the visual information in front of a visually impaired individual with the sense of touch as a reflection in his mind. It is known that ERM motors are widely used in some applications where vibration is desired, such as smart watches and other wearable devices [17, 49, 56]. LRA motors are also called linear vibration motors; such motors can be operated with lower voltage levels and lower current values [15, 49, 56]. Another component is the piezoelectric transducers; these types of components can be controlled easily and are superior in terms of their sensitivity compared to LRA and ERM motors [24]. Yet, the cost of such components is approximately 6 times higher than other components [42, 55]. In this study, ERM type vibration motor is preferred since the driver of a motor working with DC voltage can be built in a very fundamental structure.

To summarize, in this project, it is aimed to acquire images of surrounding with a camera placed on the head and perform image processing techniques to the images acquired. Moreover, it is aimed to develop a code that is suitable for this purpose so that the actuators function properly and generate the desired signal. The pixel information of resulting processed image is transmitted to the actuators and the signal is expected to generate a simplified image of the surrounding of the user with a sense of touch in the forehead region.

The variety of the previous studies is originating from different combination of certain parameters: the actuator type used, type of the sensory substitution device, the body region utilized for sensory substitution, and the image processing technique. The different combination of these parameters results in different SSDs. Therefore, in this study, ERM type electromechanical actuators, tactile-vision SSD on the forehead, and performing grayscale conversion and thresholding of the images acquired through camera are aimed to be utilized. The stated combinations of parameters establish the originality of this study and to our knowledge, there is no other study in the literature that consists of all these properties.

3 MATERIALS AND METHODS

3.1 Materials

Machine and equipment requirements are explained in detailed in this section. The name, brand, model, and requirements for each component with their technical properties are provided in Table 1. Furthermore, the consumable materials are specified and explained in detailed in Table 2.

Table 1. Machines and Equipment

Name / Brand / Model / Piece	Requirement of Use	Technical Specifications
Processor kit/ Raspberry Pi Mini Kit / RP 4 Model B / 1	Raspberry Pi, which is planned to be used as a processor, and its required electronic equipment such as camera, for the functioning of the system.	1 x Raspberry Pi 4 Model B - 8GB / 1 x Original Raspberry Pi 4 Enclosure Box / 1 x Raspberry Pi 4 Licensed Power Adapter-5V/3A-Type C / 1 x Sandisk Ultra 32Gb Class10 98MB/s MicroSD / 1 x Micro HDMI Cable.
Adapter / Socket Type / 1	It ensures that the motors used in the circuit are fed from an external source and prevents them from being unstable.	It works with 220V AC input. It provides the necessary power supply to the device with its outputs in various voltage ranges. This adapter has a value of 9V 1A.

Table 2. Consumables

Name	Requirement of Use
Soldering Wire / PINAX 30/70 / 1	It will be used for soldering electronic components.
Mounting Cable / 2	It will be used to establish the connection of electronic components.
Red LED / 100	The was used for visual purposes to observe which motor was driven and to control the running status of the software.
AMS1117-3.3	It was used in the circuit to convert 5 volts to 3.3 volts.
PCA9685PW	It is an integrated circuit used to control the speeds of the motors separately.
ULN2003	It is a high-current transistor array used to drive motors.
C0625B001L	The vibration motor
Capacitors	It is used to provide the instantaneous power needs of the circuit and balance the voltage.
Resistors	It is used to limit current and keep some integrated circuits at a certain logic level.

3.2 Methods

3.2.1 Circuit design and simulation

Required components for the generation of sensory substitution device was provided in Section 2.2.1. The type of components determined to be used in the proposed project can be listed as (1) a camera, (2) a processor, (3) a driving circuit, and actuators (Figure 5).

The sensory substitution device, which was developed in this project, falls into the category of tactile-vision substitution devices. Hence, the type of the actuator was determined according to its capability of generating tactile stimulation on the forehead of users. In order to determine the appropriate actuator, first of all, the tactile stimulation components used in the literature were investigated.

3.2.1.1 Actuator types

The components specified in Section 2.2.1 were ERM motor [3, 48, 59], LRA [3, 18,59] and piezoelectric transducers [3, 37, 59]. These components differ in their working principles and materials. Hence, there are both positive and negative aspects of each type of actuator.

LRA is controlled by AC voltage, it can be two times more powerful and consume 50% less power with the drivers of "Texas Instruments" company. Yet, the special type of driver for optimal control of LRAs add extra cost to the budget.

Piezoelectric actuators are devices that produce a small displacement with a high force capability when voltage is applied [63]. Piezo motors are small and produce large torques, have very high accuracy and short response time as compared to electromagnetic based actuators [64, 65] but they are relatively expensive.

On the other hand, ERM is an element that works with DC voltage and whose frequency and amplitude are interdependent. Also, it is easier to control ERMs compared to LRAs and piezo motors. Hence, in this study, ERM type vibration motor was preferred since the driver of a motor functioning with DC voltage can be created in a basic structure.

3.2.1.2 Determining the number of motors

3.2.1.2.1 Average size of forehead area in human body

In the next step of the circuit design, the number vibration motors that were required to create the tactile matrix was determined. For this purpose, firstly the average value of forehead area of human body was researched in the literature. It was found that in a previously conducted study [50] the average values of the forehead area of female and male bodies were reported. Mean height and width values of forehead area were reported as 58.3 ± 6.6 mm / 129 ± 14.4 mm and 61.4 ± 9.7 mm / 197.1 ± 18 mm, in females and males respectively [50]. On the other hand, it was crucial to consider that the reported mean values were obtained over a small group of people, hence it was not an accurate depiction of the average forehead sizes in a large population. Thus, in order to be used as a basis in this project the reported values of average forehead sizes were considered and the forehead height and width were determined as 60 mm and 144 mm, respectively. In conclusion, the determined dimensions were taken as the reference values for the usage area of the proposed integrated system in this study. Hence, the number of actuators to be used were estimated according to the reference usage area determined in this study.

3.2.1.2.2 Two-point discrimination distance on the forehead

Two-point discrimination refers to the capability to perceive the difference between two points touching the skin. Hence, it specifies the minimum distance required for registering simultaneous stimulations. The distance varies based on the specific body part being examined [66]. Since the interest of this study was to utilize forehead area of the human body for sensory substitution, it was required to found the two-point discrimination distance on the forehead. Thus, the distance at which the receptors on the forehead can distinguish between two mechanical stimulation was investigated through literature.

Multiple studies reported the two-point discrimination distance of the receptors. Hence, previously reported values were compared to determine a base value to be used in this study. Although the distance between two points that the receptors can distinguish was measured with the two-point discrimination test, the results obtained in different studies were distinct from each other. The variety in reported two-point discrimination values originates from the fact that there is not a standard method for the application of two-point discrimination test.

The reported spatial distance values on the forehead [7, 13, 46, 54, 58] were summarized in Table 3. Due to the deviations in the reported values, a precise definite value cannot be reached. Yet, in the light of the values reported, 12 mm was assumed as an average spatial distance on the forehead. As a result, the required number of actuators was estimated as 36 by considering the previously determined forehead height-width dimensions (144 – 60 mm), the two-point discrimination distance (12 mm) and the diameter of vibration motors used which was 8 mm. The designed motor matrix can be seen in Section 3.2.1.3., Figure 7.

Table 3. The distance at which forehead receptors can distinguish between two mechanical factors

Study	Two-point discrimination distance (mm)
[46]	8.8
[13]	9 – 15
[54]	18
[7]	14.44 - 15
[58]	14.1 ± 2.1 - 16 ± 3.2

3.2.1.2.3 Designing the test circuits

Pulse Width Modulation (PWM) was utilized for controlling the speed of ERM motors. The response time of ERMs was reported in the catalogs as 40 milliseconds (ms). A matrix of 36 (4 rows * 9 columns) vibration motors placed on the prototype was divided into 6. Motors were scanned sequentially along the columns of the matrix. It was considered to allocate 60ms for each column and to scan the matrix in 540 ms in total.

The test circuit (Figure 6) was designed for simulation of the device. For this purpose, it was determined to use LEDs for circuit simulation before constructing the motor matrix. Therefore, the designed circuit can be tested by evaluating the light emission obtained from the LEDs. If the LEDs would not emit light, then the circuit should be reevaluated. On the other hand, light emitting LEDs indicate that the circuit is functioning properly, and this designed circuit can be built for device prototype. Depending on proper functioning of the test circuit, the circuit proposed for designed tactile-vision sensory matrix was built.

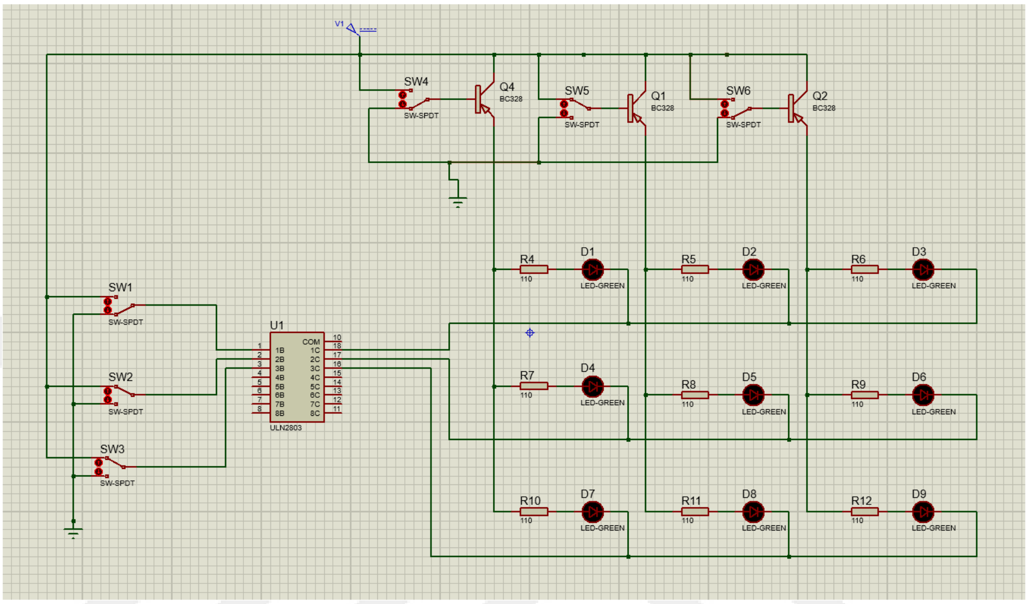

Figure 6. Schematic of designed test circuit

The printing circuits were created in digital environment and the designed electronic cards were produced. The PCB layout of the motor matrix was shown in Figure 7.

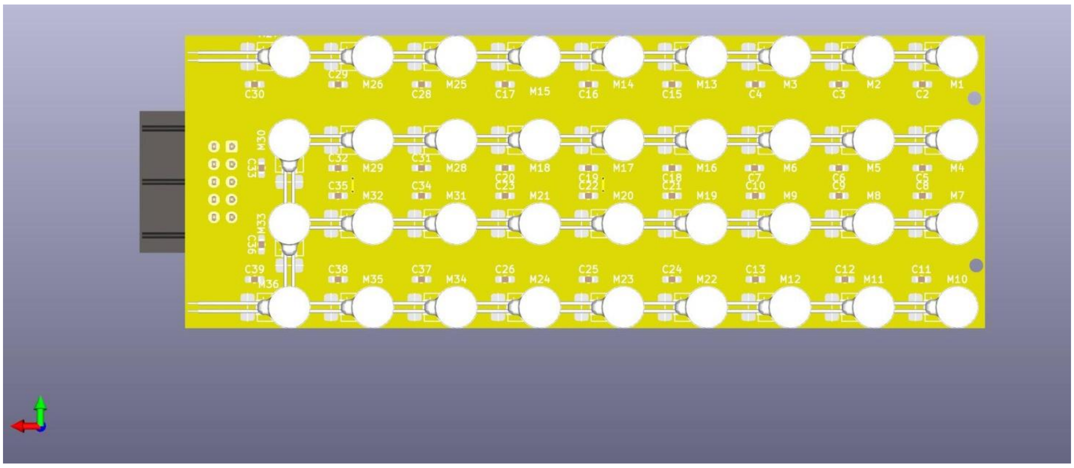

Figure 7. The designed vibration motor matrix

Vibration motors with the smallest size were planned to be used in the beginning of this study. However, the cost of motors increases as the radius decreases. Hence, vibration motors with 8 mm radius were used in this study. As a result, the number of motors was calculated as 36, based on the determined average size of a forehead and the two-point discrimination distance. The motor matrix was constructed as 4x9. The final design of the motor circuit was shown in Figure 8 and 9.

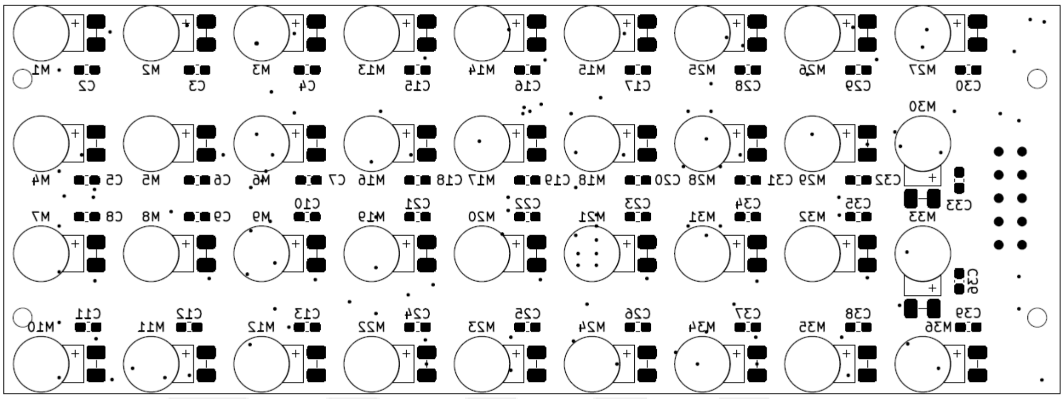

Figure 8. The motor matrix

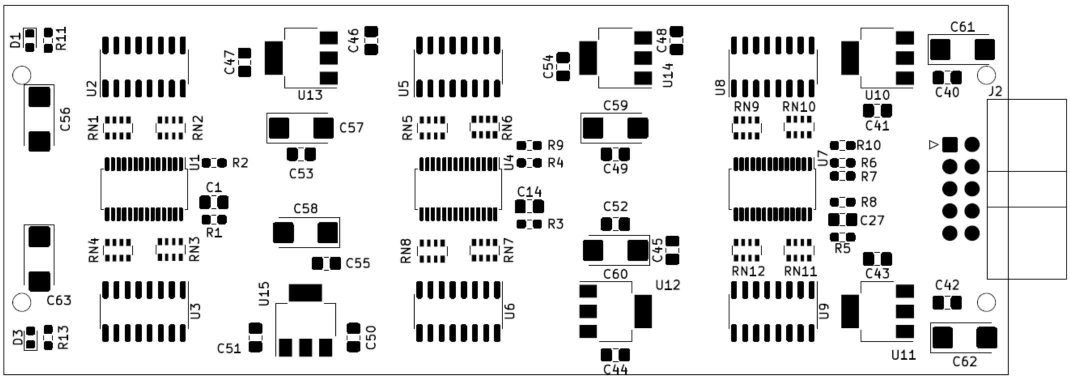

Figure 9. The rear components of the printed motor circuit

3.2.2 Circuit fabrication

As the main subject of the study, the first values to be obtained were the pixel values read from the camera and obtained by the RP. The pixel values obtained was aimed to be transmitted as a string to the Raspberry Pi. In order to convert these values to work, first of all, LED array was used instead of vibration motors. Therefore, a test PCB circuit (Figure 6) was built and 36 LEDs were placed on this circuit as 4x9 matrix.

The brightness of the LEDs was set according to gray-level pixel values of the images acquired through camera. In this way, the pre-test part of the study was carried out. The image of the test circuit built with LEDs can be seen in Figure 13.

After the preliminary test, a second printed circuit board for motor matrix was designed. Here, ERM vibration motors were used instead of LEDs. The purpose of constructing this circuit was to examine the operating characteristics of the actuators; thus, the necessary software and hardware arrangements were aimed to be performed. The designed circuits to be printed were created in digital environment, and the components were processed and soldered onto the PCB. Motor matrix produced can be seen in Figure 14 and Figure 15.

3.2.3 Electronic characterization of the integrated system

In this study, the control of DC-operated ERM motors constitutes the main part of the electronic structure. The scanning method was used in order to provide a visual intuition to the person via vibration generated from the 4x9 actuator matrix. Each column was grouped within itself. One BD138 PNP transistor belonging to these groups was used. Thus, the desired column row can be fed with "(+)" (positive). ULN2803 bipolar transistor IC was used to change the motors in the columns "(-)" (negative). It was considered that 60 ms (milliseconds) should be allocated for signal transmission of each column.

3.2.4 Software design

An appropriate software development was required for the tactile-to-vision substitution system to operate properly. Concisely, the purpose of this study was to utilize vibrotactile stimulation to achieve visual substitution in visually impaired people. Hence, utilizing the information contained in the processed camera images was the key to achieving this objective. Therefore, an appropriate image processing algorithm was programmed in Python language to process the images acquired from the camera. Additionally, MATLAB was also used for image processing purposes. Then, the processed images were utilized to operate the vibration motor matrix.

The images captured in Blue-Green-Red (BGR) format due to usage of OpenCV, which is an open-source computer vision library. Then, images were converted from BGR to grayscale. The pixel values of grayscale images were quantized to generate corresponding voltage value required to operate the vibration motors.

Furthermore, different thresholding techniques were adopted for removing noise in the grayscale images and dividing the grayscale images into various regions based on the intensity levels. The main purpose was to extract and localize the similar information in the image according to the pixel intensity values [70]. Then, obtained pixel values were quantized and mapped to the vibration motor matrix. The images were resized to match the size of the vibration motor matrix which was 4x9. The averaging technique was adopted for resizing the images. Once the image size was matched with the vibration motor matrix, the information contained in the images can be used to operate corresponding vibration motors. Operation of motors was achieved by utilizing the brightness values in the image pixels. The vibration frequency of the motors was set according to the brightness value of the corresponding pixels. The workflow of the software designed was shown in Figure 10.

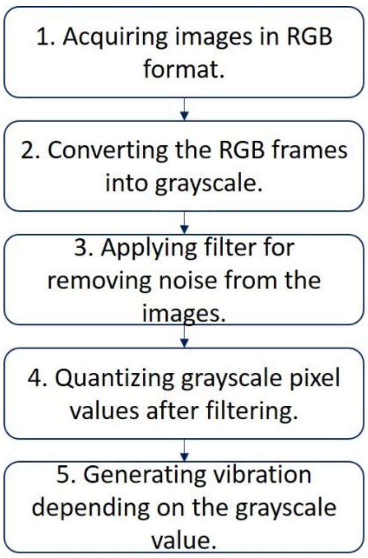

Figure 10. The image processing algorithm

Filtering of the images performed to segment the images into similar regions based on the grayscale values by obtaining optimum threshold values. Briefly, image segmentation is the process of getting objects in the image area or dividing images into several areas with each object or areas having similar attributes. Furthermore, thresholding is a simple but effective technique for image segmentation [71]. Image thresholding involves dividing an image into two or more regions based on intensity levels, allowing for analysis and extraction of desired features [72, 73]. In this study, the objective of segmenting the images was to divide the images into several areas having similar attributes. This method was adopted for creating similar groups within the image based on the pixel intensity values. Since the pixel intensity values represent the brightness values, the main purpose of the segmentation through thresholding was to navigate visually-impaired users based on the brightness values within the image. Hence, for this purpose different filtering techniques were applied. Filtering was applied to remove noise and to observe the change in grayscale pixel values due to thresholding methods used in each filtering technique. In addition to noise removal, thresholding was applied to investigate its effects on the differentiation of similar regions in the image based on the pixel intensity values. Briefly, adaptive thresholding, Gaussian filtering, adaptive-Gaussian filtering, and Otsu's thresholding methods are applied to the images acquired from the camera. Each technique has its thresholding method and the effectiveness of the techniques applied are examined.

Image thresholding segments a digital image based on a certain characteristic of the pixels (for example, intensity value). The goal is to create a binary representation of the image, classifying each pixel into one of two categories, such as "dark" or "light." Adaptive thresholding is a form of thresholding that takes into account spatial variations in illumination [74]. It scans a small set of neighboring pixels at a time, computes an optimal threshold for that specific local region, and then changes the threshold dynamically over the image. This method allows us to handle cases where there may be dramatic ranges of pixel intensities and the optimal value of threshold may change for different parts of the image [75]. The general assumption that underlies all adaptive and local thresholding methods is that smaller regions of an image are more likely to have approximately uniform illumination. This implies that local regions of an image will have similar lighting, as opposed to the image as a whole, which may have dramatically different lighting for each region [75]. Examining small regions within the image yields an optimal threshold for each region and the threshold value for each region has a weight in the overall equation used to compute an optimal threshold for the image. Thus, adaptive thresholding was used to obtain better thresholding on the images that contain non-uniform illumination.

In the Gaussian filtering method, a weighted mean is calculated for nearby pixels according to the Gaussian distribution. The gray levels of an image are transformed into binary values based on the calculated mean [76, 77]. The method involves defining a threshold based on the mean and standard deviation of the gray levels in the image. This thresholding technique is effective in removing Gaussian noise from an image.

In the Gaussian adaptive thresholding method, the working principle of adaptive thresholding is combined with the working principle of Gaussian thresholding. Therefore, each region is assigned a threshold based on a weighted average of the pixel values in the block, where the weights are a 2D Gaussian centered in the middle [78]. As a result, both noise removal and adaptive thresholding was performed simultaneously.

Lastly, Otsu's thresholding technique was used in this study. This thresholding methos was proposed by Japanese researcher Nobuyuki Otsu. It is an adaptive threshold determination method and it automatically calculates the optimum threshold [82]. The algorithm operates under the assumption that the image contains only two main classes which are foreground and background. Hence, the objective of this method is to separate image into two classes, foreground, and background, based on the grayscale intensity values of the pixels. The pixels with intensity values above the threshold are assigned to the foreground region while the intensity values below the threshold are assigned to the background region. Then, the optimal threshold is determined using the discriminant criterion, which aims to increase the differentiation of gray levels between classes [79, 83]. The algorithm iterates through all the credible threshold values to compute the optimum threshold and utilizes the histogram of the grayscale image during its execution. Otsu's method is well suited to histograms containing two peaks, which are referred to as bimodal. Basically, it selects a threshold value which lies in the middle of both the histogram peaks. However, Otsu's thresholding has some limitations. In case of histograms with multiple peaks, this may lead to a poor segmentation in images. It may produce inaccurate results for images with uneven illumination. The lack of robustness makes this method susceptible to noise, resulting in less precise thresholding outcomes [80]. Therefore, multi-level thresholding can be utilized to increase the quality of the segmentation [84].

Furthermore, multi-Otsu thresholding was utilized to increase the segmentation of gray levels in the image. Conventional Otsu's method computes a single threshold and the image is divided into two classes (generally foreground and background), however, multi-Otsu thresholding effectively divides the image into more than two classes or regions according to their level of pixel intensities. In this case, multiple thresholds are computed by the algorithm based on the histogram of the image. In the cases where images exhibit multiple regions with distinct intensity levels or objects, implementation of multi-Otsu thresholding is effective in accurate separation of these intensity levels [84, 85, 86]. Additionally, MATLAB was used when performing the multi-Otsu thresholding.

Moreover, in an image, foreground pixels represent the moving or changing regions while background pixels represent the regions that are static [67]. The background pixel value of each pixel appears most frequently in the pixel intensity histogram of the video sequence because the frequency of the value which comes from moving objects is usually less than that of the background [69]. The primary objective of foreground detection was to extract foreground objects from video frames and obtain feature information of foreground objects to detect usually moving objects, such as moving human bodies and vehicles [70]. Hence, accurate foreground detection allows object extraction from the background [68]. However, in this study, the images were segmented according to similar grayscale values present in the images. This information can be used in future studies for object recognition by Touch Vision.

To summarize, different filtering techniques were applied to obtained images to examine the impacts of thresholding on the differentiation between grayscale values. Then, the vibration signal was generated according to the brightness value of the pixels. The pixel values of gray-scale images acquired were quantized in the software, then obtained values were mapped to the vibration motors as frequency value. Thus, brightness value of the pixels was correlated with the frequency of the vibration motors. For instance, the frequent vibration of motors indicates that there is a bright area, or the less frequent vibration indicates the darkness. Therefore, visually impaired user could understand their surrounding by evaluating the vibration frequency of the actuators.

The code for image processing is shown in Figure 11 and Figure 12. As mentioned above paragraphs, various filtering techniques are applied. Namely, adaptive thresholding, Gaussian filtering, adaptive-Gaussian filtering, and Otsu’s thresholding methods are applied to the images acquired from the camera. Each technique has its own thresholding method and the effectiveness of the techniques applied were observed.

```python
@author: Necibe
"""

import cv2

width = 9
height = 4
dim = (width, height)

width = 450
height = 200
dim2 = (width, height)

cap = cv2.VideoCapture(0)

while(True):
    ret, img = cap.read()

    cv2.imshow('Original frame', img)
    filename = 'OriginalImage.jpg'
    cv2.imwrite(filename, img)

    #Gray-scale Conversion
    gray = cv2.cvtColor(img, cv2.COLOR_BGR2GRAY)
    #print(np.array(gray, dtype=np.int8))
    cv2.imshow('Gray-scaled frame', gray)
    resized = cv2.resize(gray, dim, interpolation = cv2.INTER_AREA)
    resized2_gray = cv2.resize(resized, dim2, interpolation = cv2.INTER_AREA)
    cv2.imshow('resized2', resized2_gray)
    filename_gray = 'GrayImage.jpg'
    cv2.imwrite(filename_gray, gray)
    filename_gray_matrix = 'GrayImage_matrix.jpg'
    cv2.imwrite(filename_gray_matrix, resized2_gray)

    #Adaptive Thresholding
    adapt = cv2.adaptiveThreshold(gray,255, cv2.ADAPTIVE_THRESH_MEAN_C,cv2.THRESH_BINARY, 13, 0)
    cv2.imshow('Adaptive', adapt)
    resized_adapt = cv2.resize(adapt, dim, interpolation = cv2.INTER_AREA)
    resized2_adapt = cv2.resize(resized_adapt, dim2, interpolation = cv2.INTER_AREA)
    cv2.imshow('resized2_adapt', resized2_adapt)
    filename_adapt = 'AdaptiveImage.jpg'
```

Figure 11. The image processing code (part 1)

```python
    cv2.imwrite(filename_adapt, adapt)
    filename_adapt_matrix = 'AdaptiveImage_matrix.jpg'
    cv2.imwrite(filename_adapt_matrix, resized2_adapt)

    #Adaptive-Gaussian Thresholding
    adapt_gauss = cv2.adaptiveThreshold(gray,255,cv2.ADAPTIVE_THRESH_GAUSSIAN_C,cv2.THRESH_BINARY, 13, 0)
    cv2.imshow('Adaptive Gaussian', adapt_gauss)
    resized_adapt_gauss = cv2.resize(adapt_gauss, dim, interpolation = cv2.INTER_AREA)
    resized2_adapt_gauss = cv2.resize(resized_adapt_gauss, dim2, interpolation = cv2.INTER_AREA)
    cv2.imshow('resized2_adapt_gauss', resized2_adapt_gauss)
    filename_adapt_gauss = 'AdaptGaussImage.jpg'
    cv2.imwrite(filename_adapt_gauss, adapt_gauss)
    filename_adapt_gauss_matrix = 'AdaptGaussImage_matrix.jpg'
    cv2.imwrite(filename_adapt_gauss_matrix, resized2_adapt_gauss)

    #Gaussian Thresholding
    blur = cv2.GaussianBlur(gray, (3, 3), 3)
    #print(np.array(blur, dtype=np.int8))
    cv2.imshow('Gaussian filtered', blur)
    resized_gauss = cv2.resize(blur, dim, interpolation = cv2.INTER_AREA)
    resized2_gauss = cv2.resize(resized_gauss, dim2, interpolation = cv2.INTER_AREA)
    cv2.imshow('resized2_gauss', resized2_gauss)
    filename_gauss = 'GaussianImage.jpg'
    cv2.imwrite(filename_gauss, blur)
    filename_gauss_matrix = 'GaussianImage_matrix.jpg'
    cv2.imwrite(filename_gauss_matrix, resized2_gauss)

    #Otsu's Thresholding
    ret, otsu_s = cv2.threshold(gray, 0, 255, cv2.THRESH_BINARY + cv2.THRESH_OTSU)
    cv2.imshow('otsu', otsu_s)
    resized_otsu = cv2.resize(otsu_s, dim, interpolation = cv2.INTER_AREA)
    resized2_otsu = cv2.resize(resized_otsu, dim2, interpolation = cv2.INTER_AREA)
    cv2.imshow('resized2_otsu', resized2_otsu)
    filename_otsu = 'OtsuImage.jpg'
    cv2.imwrite(filename_otsu, otsu_s)
    filename_otsu_matrix = 'OtsuImage_matrix.jpg'
    cv2.imwrite(filename_otsu_matrix, resized2_otsu)

cap.release()
cv2.destroyAllWindows()
```

Figure 12. The image processing code (part 2)

4 RESULTS

4.1 Circuit Fabrication

The image of the test circuit built up with LEDs is attached in the Figure 13. The circuit was tested and it was observed that the LEDs were working properly. The brightness of the LEDs was set according to gray-level pixel values of the images acquired through camera. It was observed that the test circuit was functioning properly and it was estimated that the designed motor matrix could operate properly as well.

Figure 13. Printed LED test circuit

Subsequently, the printed circuit board for motor matrix is tested. The manufactured circuit can be seen in Figure 14 and Figure 15. Test results demonstrated that while one motor is vibrating, the rest of the circuit is vibrating as well.

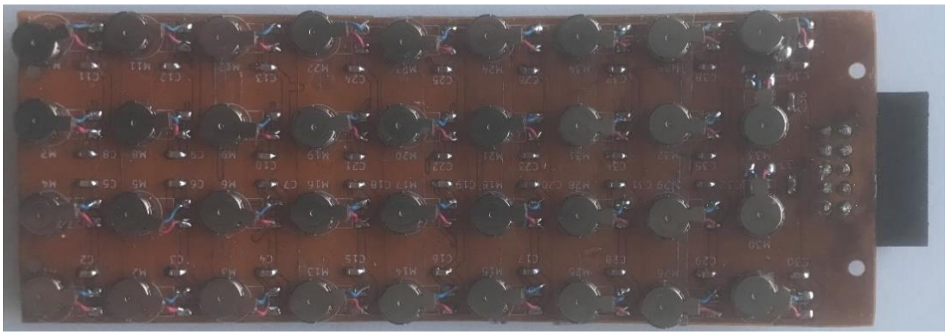

Figure 14. The motor matrix produced

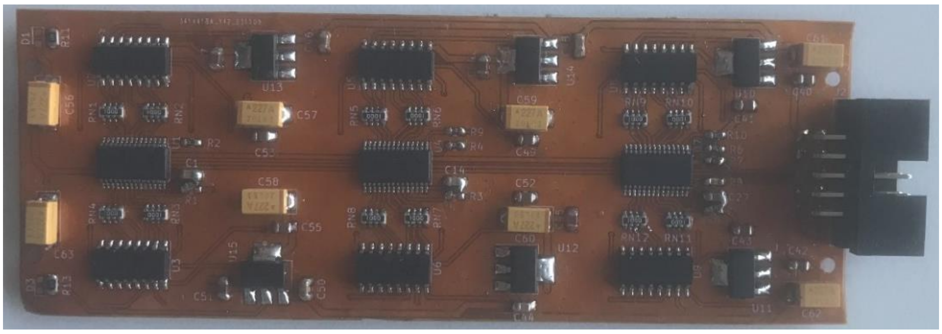

Figure 15. Rear view of the motor matrix produced

4.2 Acquired Images

The example images were taken by the integrated camera of the computer. Since the acquired images were used to be utilized for obtaining brightness values to operate vibration motors, the image processing code was run to obtain these values for the control of vibration motors.

4.2.1 Demonstration of the image processing software

As stated in the Section 3.2.4, the images acquired were converted to gray-scale and then the brightness values of the pixels of the image were quantized. In this study, it was proposed that visually impaired users can navigate through the environment by interpreting the vibration frequency of each motor, since high frequency vibration denotes bright area while the low frequency vibration denotes dark pixels.

First, the code was tested in the computer platform. Three images are acquired for demonstration and image processing was performed. The obtained results were shown in below. In this section, the first two steps of the image processing algorithm shown in Figure 10 were performed. Then, the change in gray-scale values of the pixels in each image were observed.

The images are numbered as Frame 1, Frame 2 and Frame 3 for simple representation. The original color image was acquired through camera, then converted into gray-scale image and the image was resized for matching the motor matrix 4x9.

Averaging of the pixels were performed when resizing the images. The acquired and obtained images were shown in below. The resized image represents the pixel values of the gray image. As mentioned above, the change in the brightness of the pixels was observed as the camera moving through right. The chair in the images (Figure 16, 19, 22) can be selected from the resized gray matrices (Figure 18, 21, 24), as camera moves to the right. Therefore, it can be concluded that the developed system can be used to navigate based on the brightness and darkness in the environment. While, high brightness denotes that the proceeding is safe, the darkness indicates that users should be precautious.

The system was also tested when the vibration motors were connected to Raspberry Pi. It was successfully working; the users could be able to differentiate the bright area in the environment based on the vibration frequency of the motors.

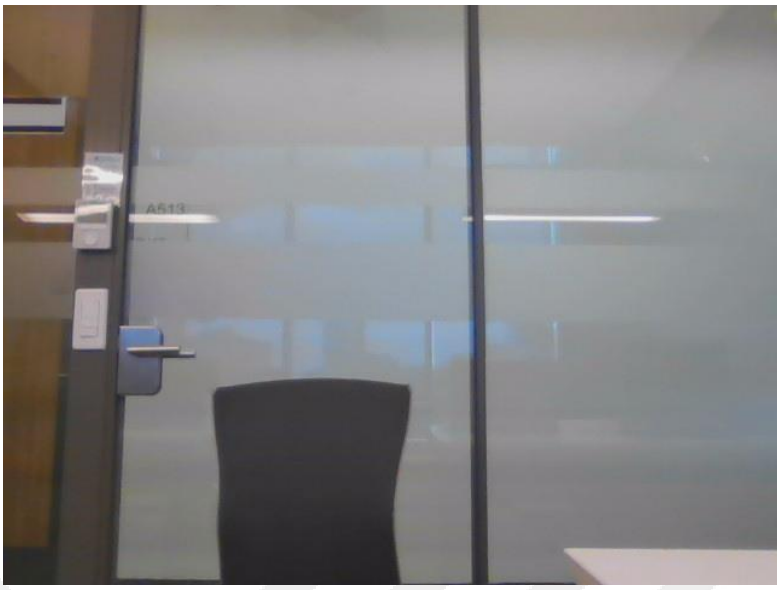

Figure 16. Original Frame 1 (color image)

Figure 17. Gray-scale image of Frame 1

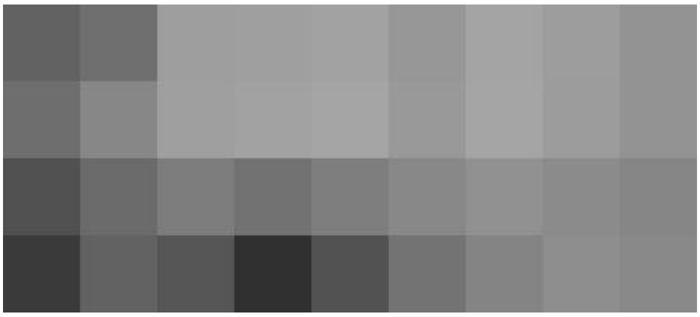

Figure 18. Resized gray-level image of Frame 1

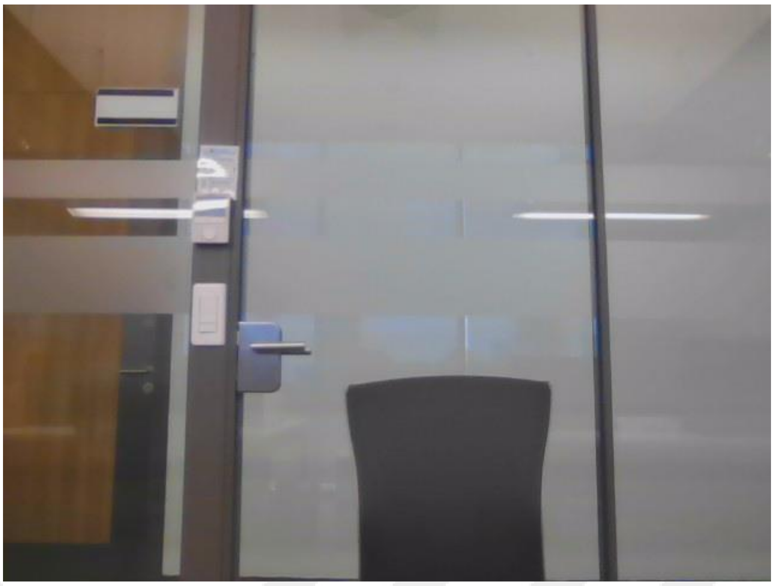

Figure 19. Original Frame 2 (color image)

Figure 20. Gray-scale image of Frame 2

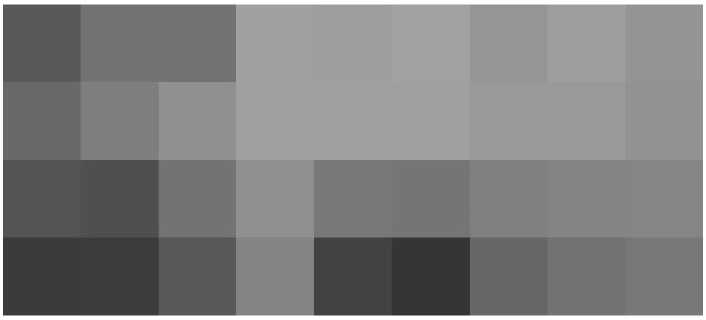

Figure 21. Resized gray-level image of Frame 2

Figure 22. Original Frame 3 (color image)

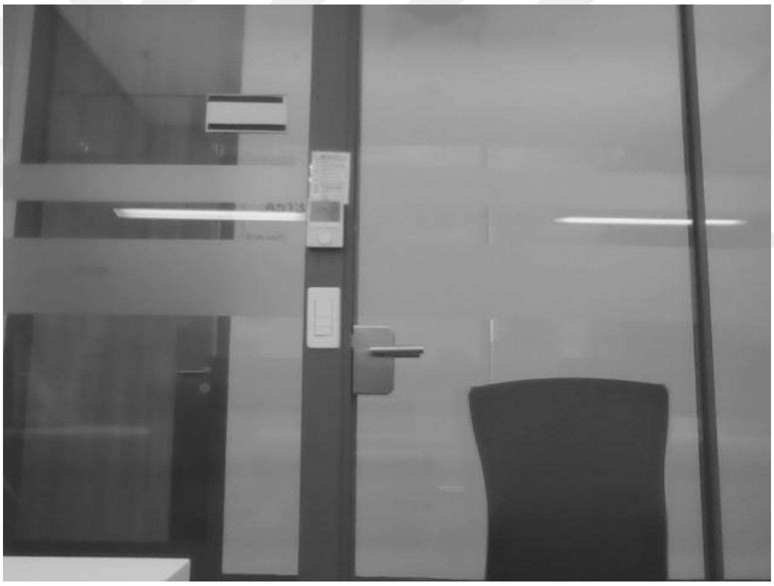

Figure 23. Gray-scale image of Frame 3

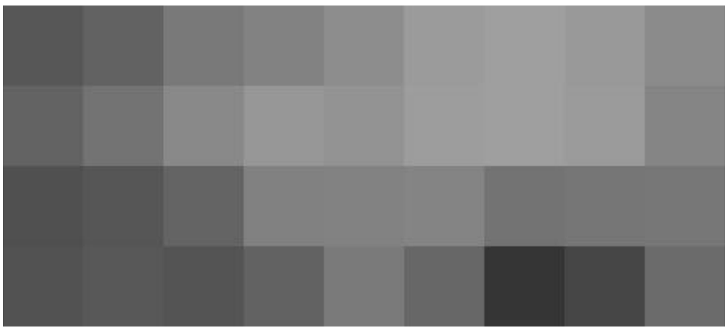

Figure 24. Resized gray-level image of Frame 3

4.2.2 Application of filtering techniques

Moreover, it was also stated (Section 3.2.4) that the differentiation of the gray levels in the images may provide more accurate information about the environment. Also, differentiation of foreground and background pixels provide information about constant and changing regions in an image. Therefore, object differentiation can be achieved by separating the distinct gray levels. Hence, in order to differentiate foreground and background pixels various thresholding techniques were applied to the images. In this section, the results of thresholding techniques that were applied to Frame 1, Frame 2 and Frame 3 can be seen.

4.2.2.1 Thresholding of Frame 1

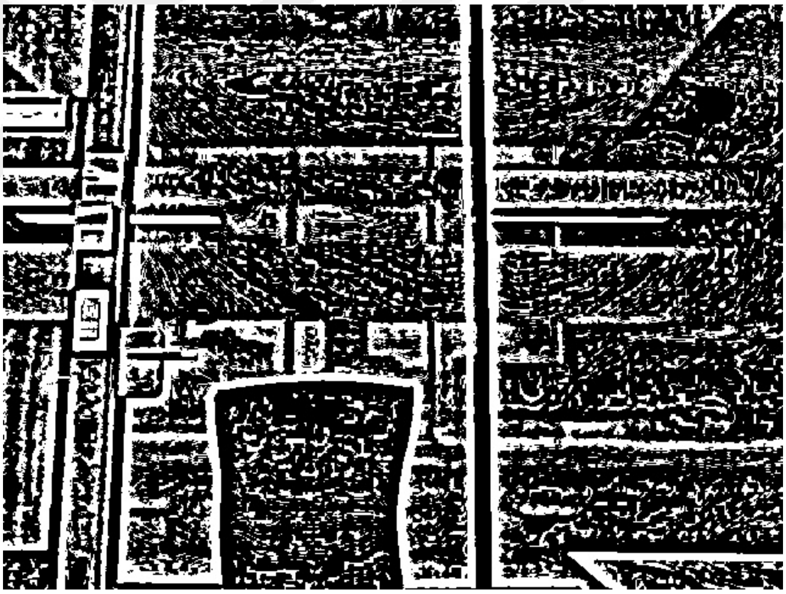

Figure 25. Adaptive thresholding of gray-scale Frame 1

Figure 26. Resized image of Figure 25

Figure 27. Gaussian thresholding of gray-scale Frame 1

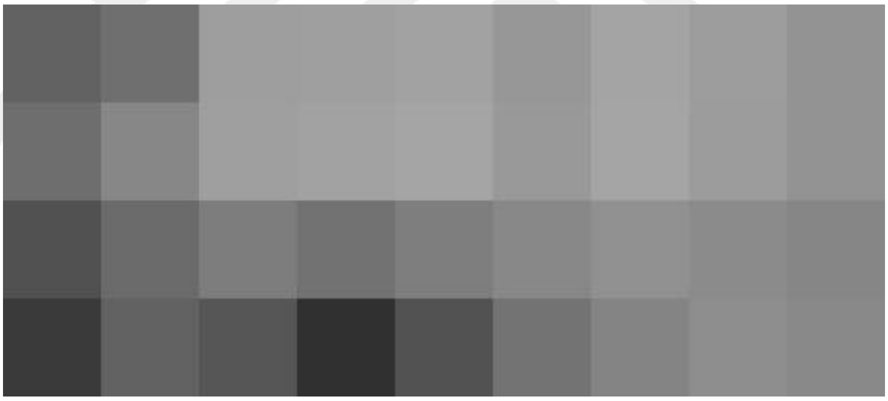

Figure 28. Resized image of Figure 27

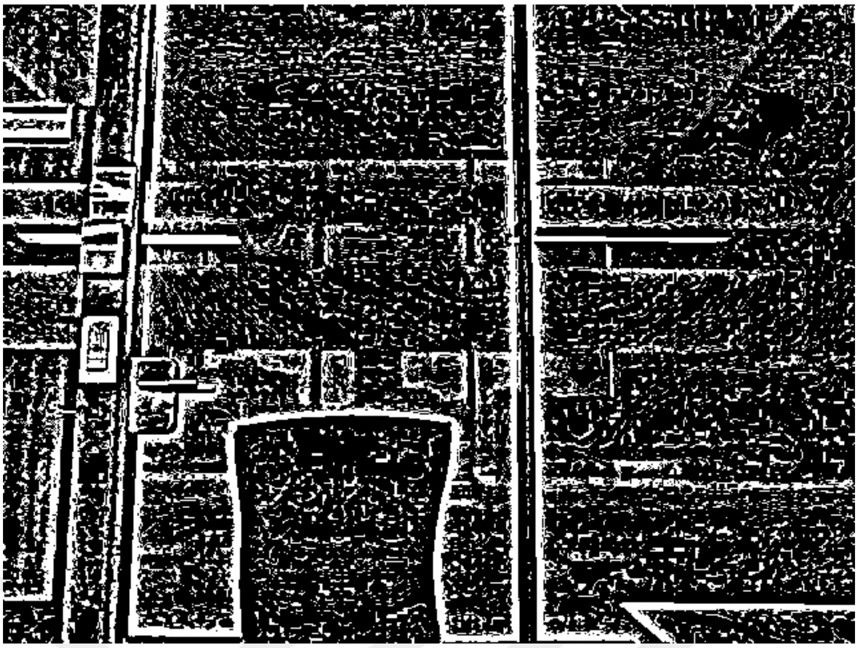

Figure 29. Adaptive-Gaussian thresholding of gray-scale Frame 1

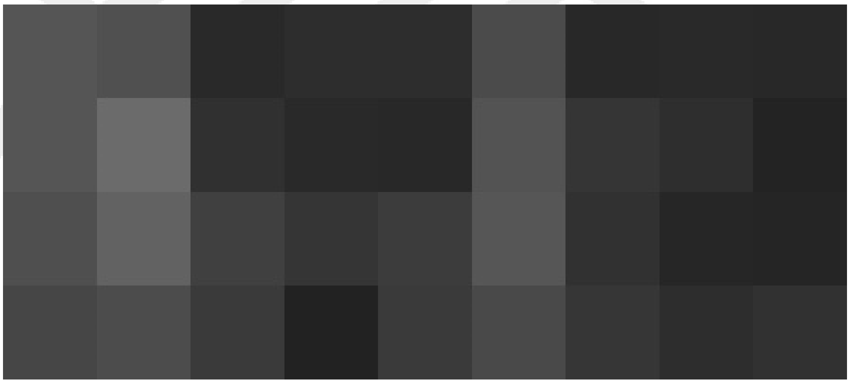

Figure 30. Resized image of Figure 29

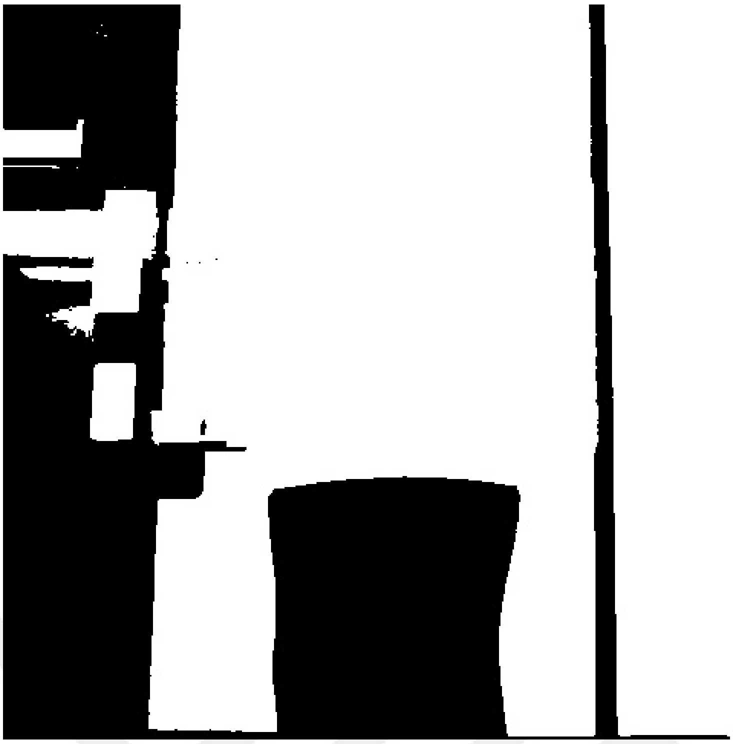

Figure 31. Otsu's thresholding of gray-scale Frame 1

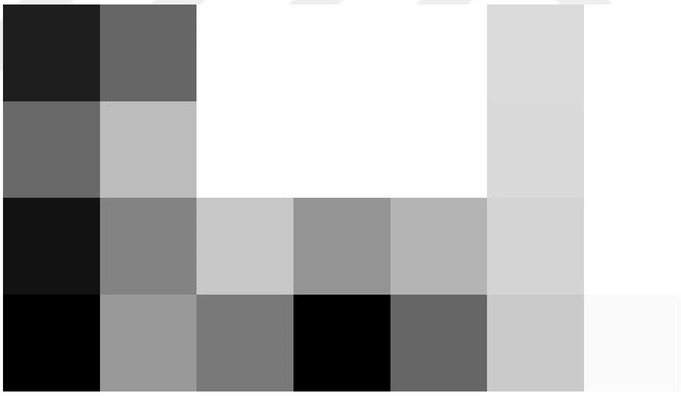

Figure 32. Resized image of Figure 31

Figure 33. Multi-Otsu thresholding of Frame 1

Figure 34. Resized image of Figure 33

4.2.2.2 Thresholding of Frame 2

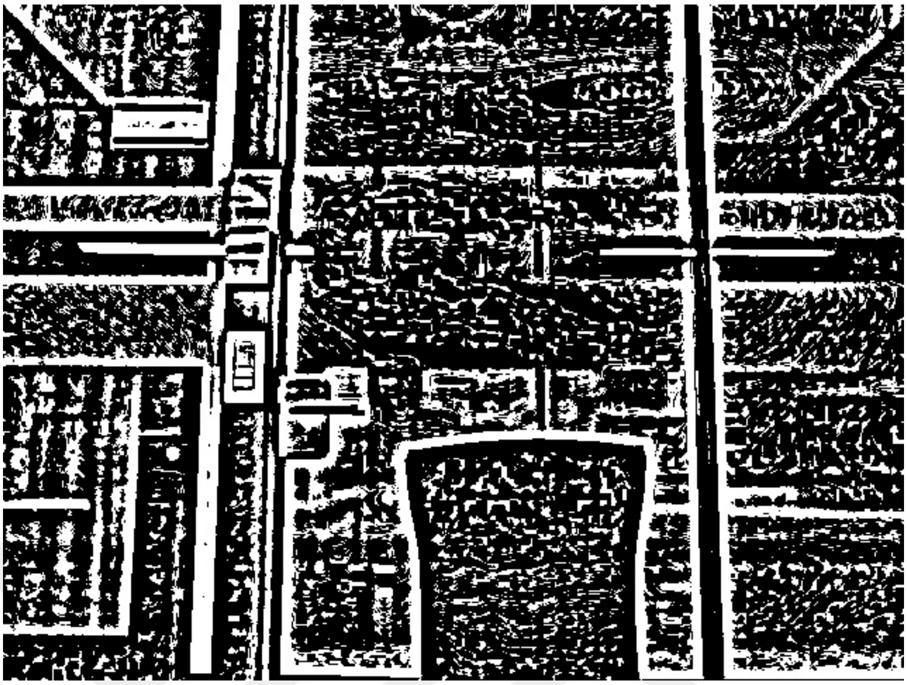

Figure 35. Adaptive thresholding of gray-scale Frame 2

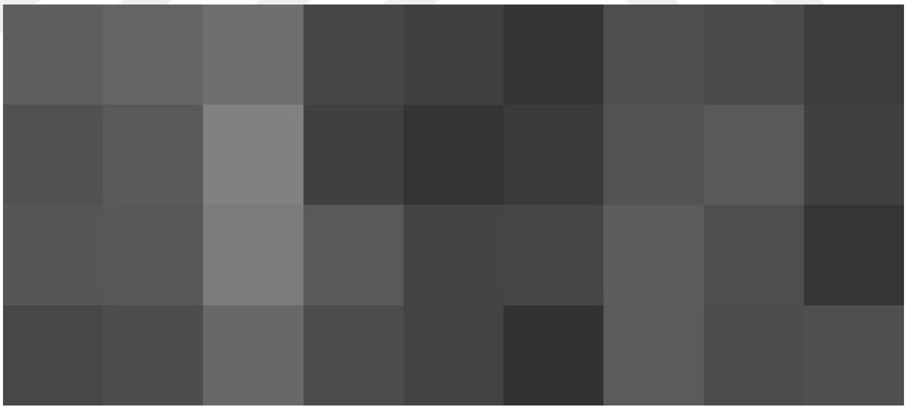

Figure 36. Resized image of Figure 35

Figure 37. Gaussian thresholding of gray-scale Frame 2

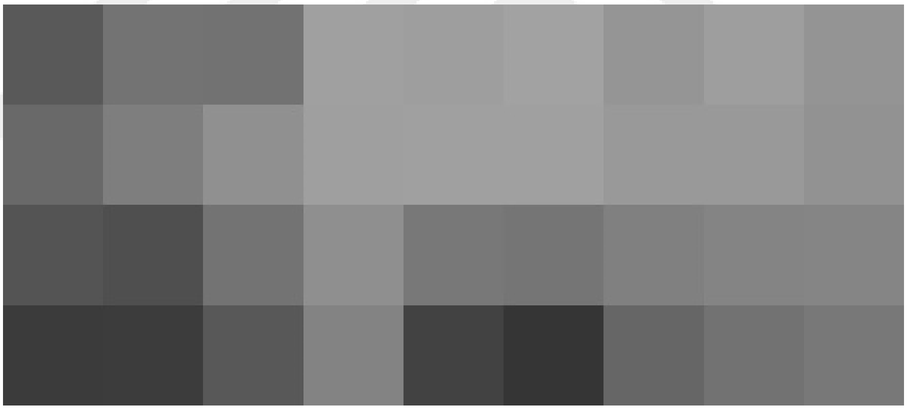

Figure 38. Resized image of Figure 37

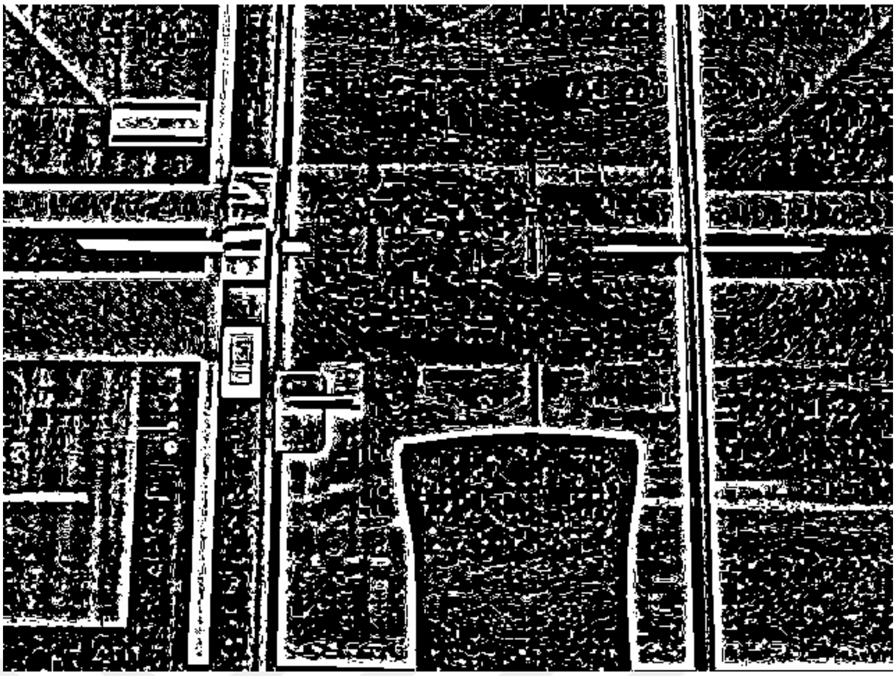

Figure 39. Adaptive-Gaussian thresholding of gray-scale Frame 2

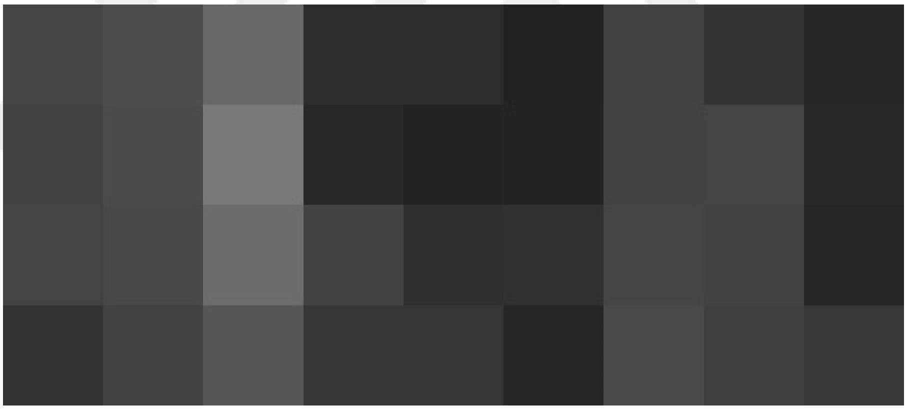

Figure 40. Resized image of Figure 39

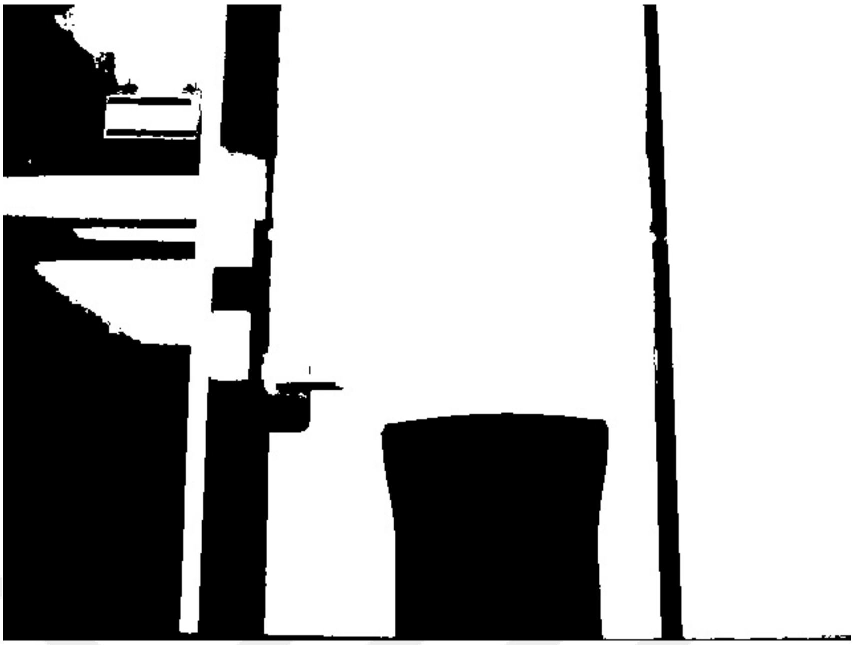

Figure 41. Otsu’s thresholding of gray-scale Frame 2

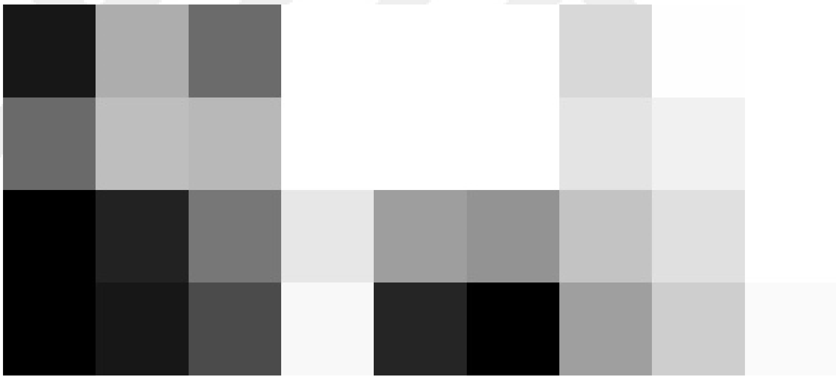

Figure 42. Resized image of Figure 41

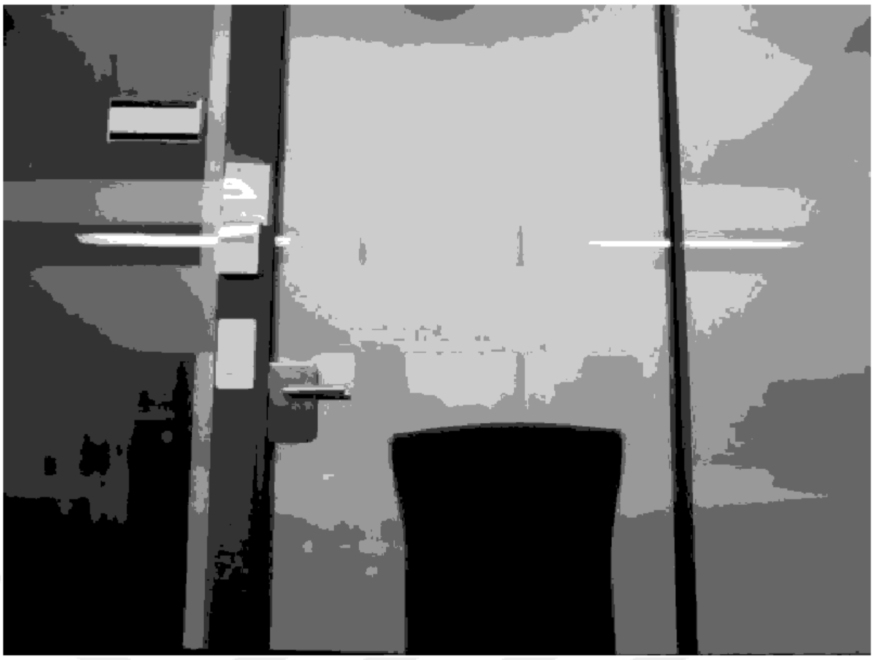

Figure 43. Multi-Otsu thresholding of Frame 2

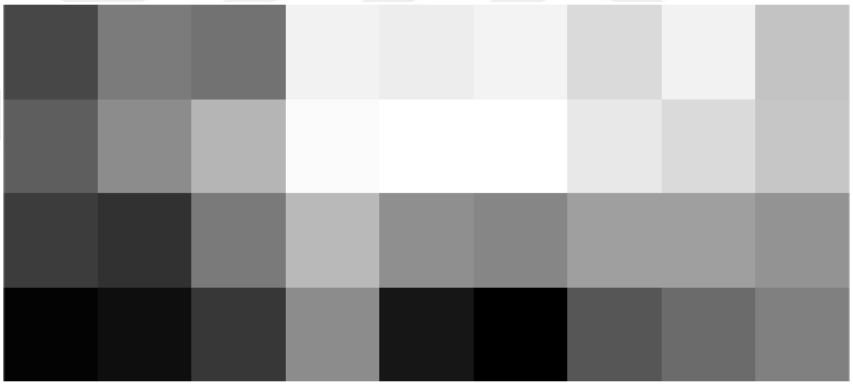

Figure 44. Resized image of Figure 43

4.2.2.3 Thresholding of Frame 3

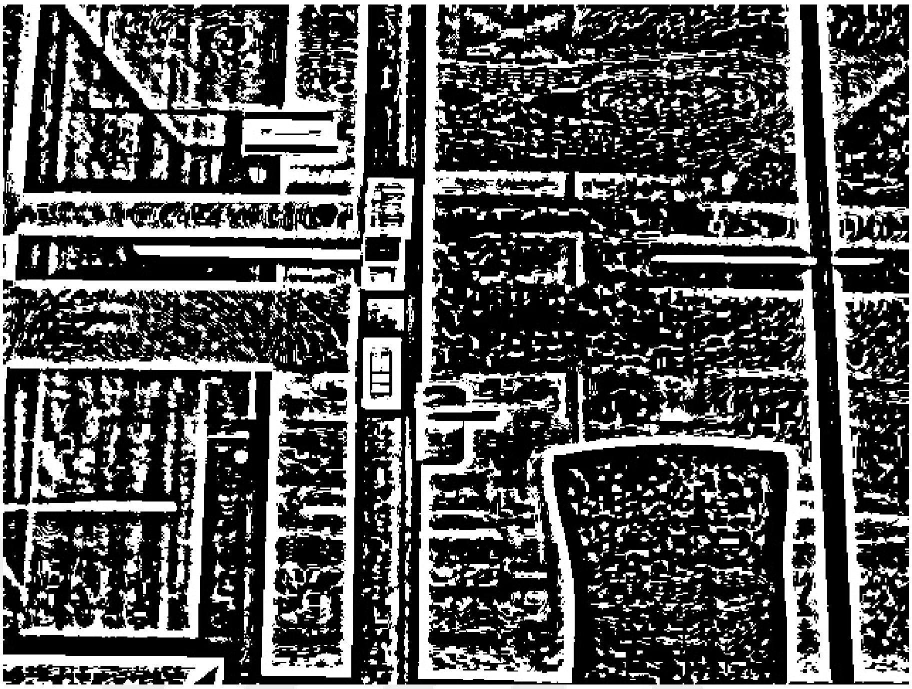

Figure 45. Adaptive thresholding of gray-scale Frame 3

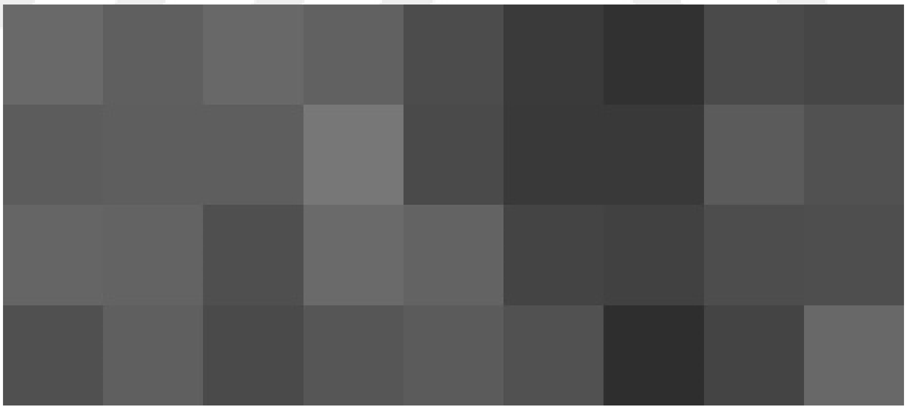

Figure 46. Resized image of Figure 45

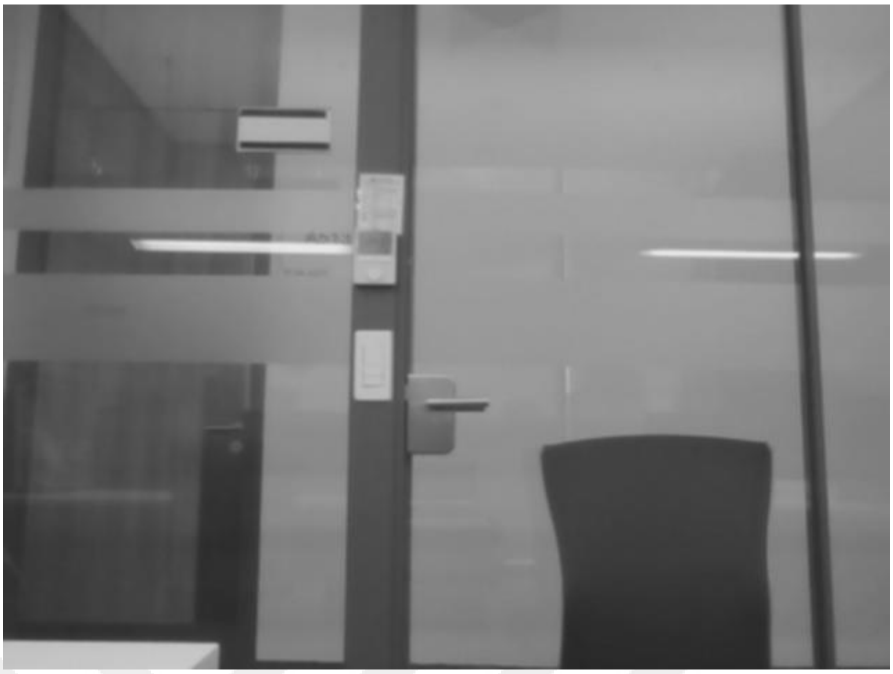

Figure 47. Gaussian thresholding of gray-scale Frame 3

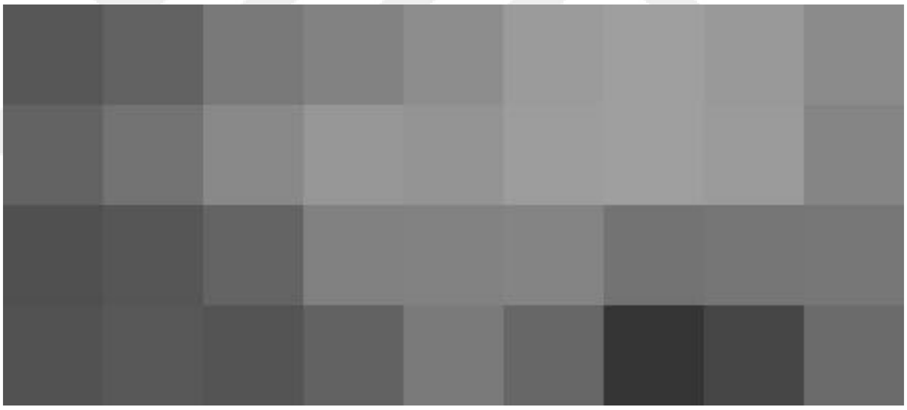

Figure 48. Resized image of Figure 47

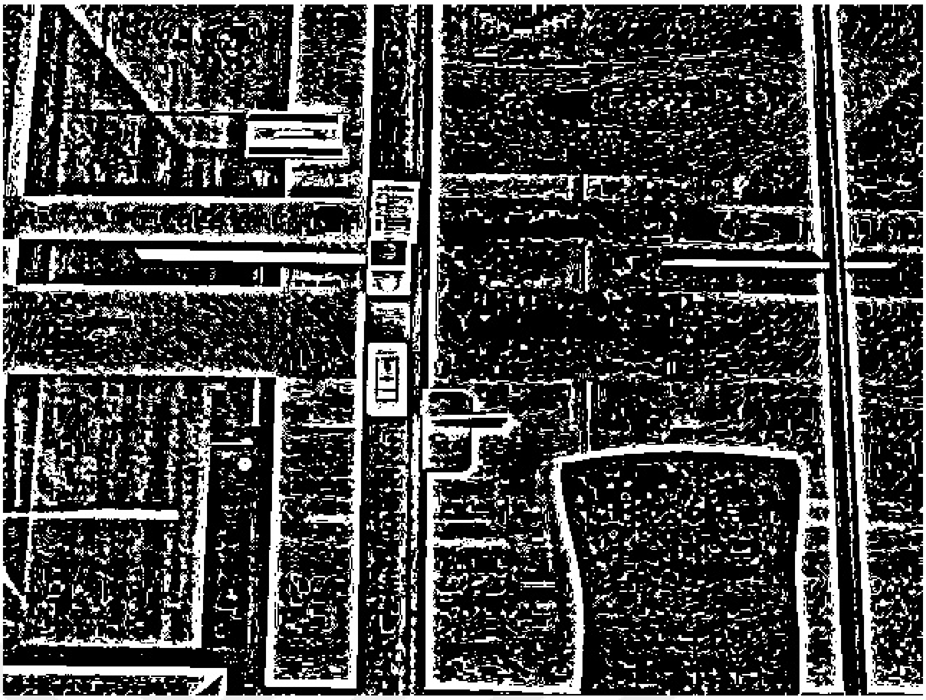

Figure 49. Adaptive-Gaussian thresholding of gray-scale Frame 3

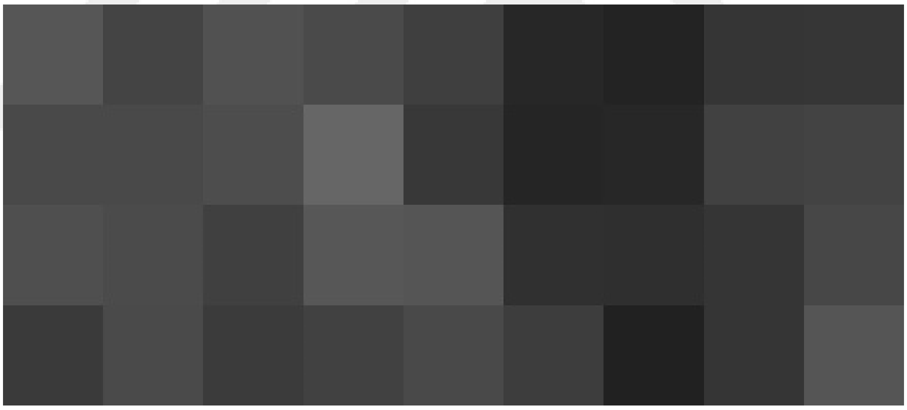

Figure 50. Resized image of Figure 49

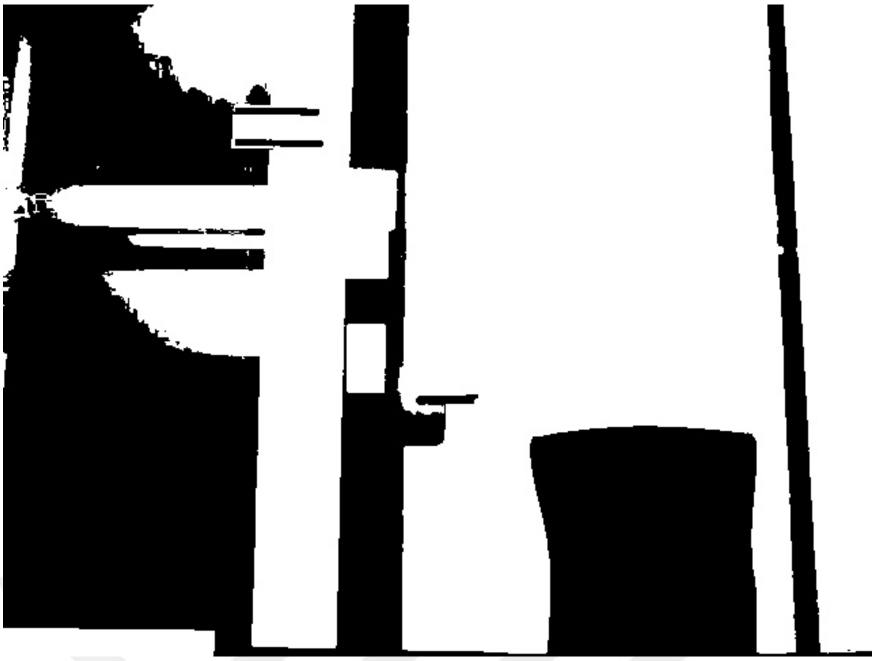

Figure 51. Otsu’s thresholding of gray-scale Frame 3

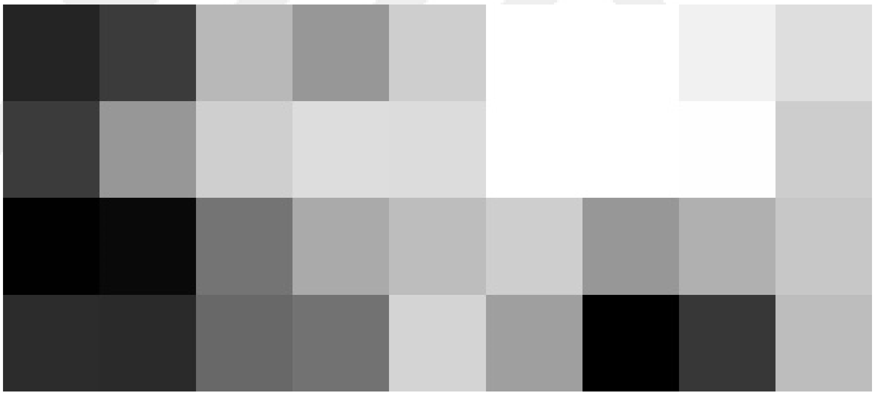

Figure 52. Resized image of Figure 51

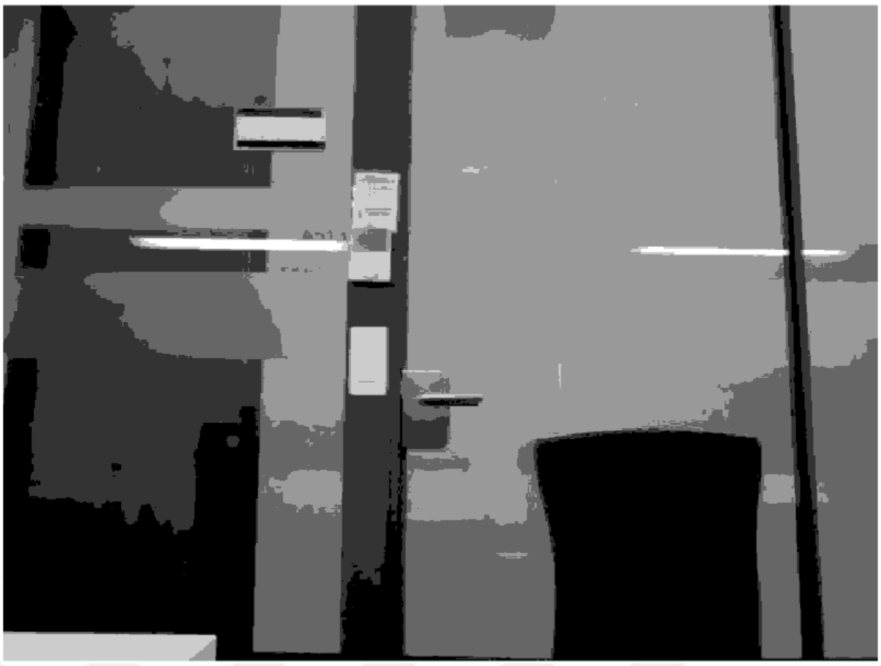

Figure 53. Multi-Otsu thresholding of Frame 3

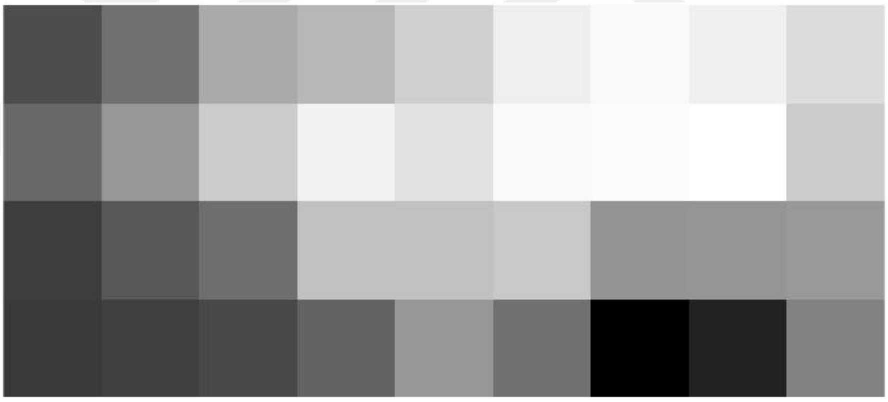

Figure 54. Resized image of Figure 53

5 DISCUSSION

5.1 Circuit Fabrication - Motor Matrix

Two different circuits were designed and built which were test and vibration motor circuit. The test circuit which is built up with LEDs had a nonoperating component in the first manufacture. However, the broken component was replaced with an operating one, then test circuit has resulted in its proper functioning.

On the other hand, in the motor matrix, the vibration of each motor was affecting the rest of the circuit. This situation prevents the independent vibration of motors and it could interfere with the effectiveness of the integrated sensory substitution system. Hence, the spreading of the vibration should be prevented and the vibration of a single motor should not interfere with the functioning of the other motors on the matrix. Therefore, it is aimed to utilize a gel pad for damping of the motors as a solution for the problem mentioned above.

5.2 Image Processing

The image processing software was tested and images acquired. As mentioned in Section 3.2.4, the conversion of the images to gray-scale was achieved and the images were resized successfully to match the size of the motor matrix which was 4x9. The obtained pixel values of gray-scale images were observed on the screen as a display. Hence, the change in the lightning of the images were observed as the Frames changes.

The acquired images were separated into two categories in the Results Section, which are The Acquired Images and Application of Filtering Techniques. Hence, the results were discussed under the related titles.

5.2.1 Discussion of The Resulted Acquired Images

In the first part of image processing, the entire image processing algorithm was not applied. This was because the effect of filtering techniques was aimed to be observed, then the results were compared with the gray-scale images without filtering applied. Hence, in this section the gray-scale images (Section 4.2.1) were discussed.

Gray-scale conversion was achieved to obtain gray-scale images from original BGR (Blue-Green-Red) images. Images were acquired in BGR instead of RGB due to usage of OpenCV as an image processing library.

The first two steps of the image processing algorithm shown in Figure 10 was applied to the images obtained in the Section 4.2.1. After gray-scale conversion of the images, the resulted image was resized to the 4x9. It was observed that the resized images demonstrate the important features in the gray-scale images (Results 4.2.1). The chair in the Frame 1, Figure 16, was also differentiable in resized gray-scale image Figure 18 as the black pixels in the middle represent it. Thus, it was demonstrated that the resizing the gray-scale image to a low-resolution image of 4x9 pixels was sufficient to contain important object features. However, the resolution can be improved if smaller vibration motors used for the sensory substitution.

5.2.2 Discussion of The Filtering Techniques Applied to Gray-Scale Images

In this section, the difference between the gray-scale images and the images filtered were compared with their respective resized images as well.

Adaptive thresholding of all of the three frames which were Frame 1, Frame 2 and Frame 3 (Figure 25, 35 and 45, respectively) and their respective resized 4x9 gray-scale images (Figure 26, 36 and 46) were observed. The filtered images were compared with the gray-scale images. It was observed that the adaptive thresholding converted the lighter gray areas into darker gray or black. It was also observed that the white pixels were almost eliminated. The white space represents that it is safe to proceed while black pixels represents that there might be an object should the user be aware of. Compared to gray-scale images of each Frame, the adaptive thresholding resulted in elimination of the white and lighter gray pixels and it converted them to darker-gray and black pixels. The ability to differentiate between the different gray levels was decreased. Hence, the important information about the objects and the free space were lost since it was resulted in poor distinction between the gray levels. Thus, in this case, it was observed that adaptive thresholding was not suitable for increasing the segmentation of the gray levels in the image. However, the parameters of thresholding method can be changed to different values and the results can be examined with different parameters.

Moreover, the resulted images after Gaussian thresholding and their respective resized images were compared to their gray-scale format. The noise removal was achieved and blurring of the features was observed in the Gaussian filtered images (Figure 27, 37 and 47). After the noise removal, it was still possible to discern between different gray levels. Also, it was observed that the obtained resized images (Figure 30, 38 and 48) consisted the important features after the averaging method. The Gaussian filtered images were compared to the gray-scale images of each Frame. It was observed that the Gaussian filtered version of each Frame was nearly identical to their respective gray-scale images.

Adaptive-Gaussian thresholding of the obtained images (Figure 29, 39 and 49) resulted in better distinction around the edge areas within the image. However, the distinction between different gray level areas was poor. Furthermore, the resulted resized images (Figure 30, 40 and 50) were dominated by dark pixels, resulted in elimination of the white and lighter gray pixels. This may cause misleading information about the different gray areas within the images.

Otsu's thresholding (Figure 31, 41, and 51) was useful in highlighting the important features in the image. However, the different gray levels in the images were separated according to the single threshold that the algorithm computed. As a result, the features were prominently distinct in this case, however, some of the information contained in the image was lost. Hence, the separation of the different classes in the image was limited. Despite the loss of information in the image, the resized images (Figure 32, 42 and 52) contain the important features, provide a distinction between the foreground and background pixels.

Multi-Otsu thresholding provide the option of determining the number of classes. Hence, different gray levels were separated into more than one class. Segmentation of the distinct gray levels were achieved via multi-Otsu thresholding.

Among all filtering methods studied, multi-Otsu's thresholding can be considered as the most suitable application for the Touch Vision device. The differentiation of several classes in images may be used to segment objects in the future studies as well. However, it would be useful to statistically measure the similarity between the filtered images and their corresponding gray images.

5.3 Suggested Modifications and Improvement of Touch Vision

When the testing of the sensory substitution system was performed, it was observed that the vibration motor matrix was operating properly and the image processing algorithm was running efficiently. However, an increase in the temperature of the circuit was observed. This may create a discomfort for users and even it may not be possible to use the device if the heat produced is over bearable amount. To solve this problem, vibration motors that produce less heat can be used. Additionally, the frequency of the motors can be decreased. When the frequency of the vibration motors was decreased from 500 PWM to 100 PWM, it was observed that the heat produced was reduced.

This observation showed us that the visual signals can be transferred to user as heat signals. It may even be possible to give information using both vibrations and heat change together to create tactile images that contain both brightness and color data simultaneously.

The device may also be improved by the help of an artificial intelligence program that evaluates the objects and tell what they are to the user's ears while visual information is transferred to the tactile device on the forehead.

6 CONCLUSION

In this study it was developed an integrated tactile-to-vision sensory substitution system for visually impaired people. Briefly, the images of surrounding were acquired with a camera placed on the head and image processing methods were applied. For this purpose, an image processing code was developed so that the actuators function properly and generate the desired vibration signal. ERM type vibration motors were used as actuators for generation of tactile-vibration on the forehead. Grayscale conversion of the acquired images was achieved to obtain brightness values within the images. The pixel information of resulting processed images was quantified and transmitted to the vibration motors as a frequency value. Based on the brightness value of the pixels in the images, the vibration was generated on the forehead of the users. Hence, the users could be able to navigate through the environment by utilizing the information provided with a sense of touch in the forehead region.

Furthermore, thresholding methods were utilized for increasing the segmentation of the different gray levels in the images. The optimization of the parameters was required for filtering of the images. However, it can be concluded that the most successful results were obtained via Gaussian and multi-Otsu thresholding method. The statistical analysis of the similarity index between the images could provide a more accurate result about the optimum thresholding method.

The objective of the study was achieved and a prototype of a tactile-vision device was developed. Further improvement of this device seems possible by an artificial intelligence program and transmittance of signal by additional senses like heat sensation.

7 REFERENCES

[1] Abboud, S., Hanassy, S., Levy-Tzedek, S., Maidenbaum, S., & Amedi, A. (2014). EyeMusic: Introducing a “visual” colorful experience for the blind using auditory sensory substitution. *Restorative Neurology and Neuroscience*, *32*(2), 247–257. https://doi.org/10.3233/RNN-130338

[2] Bach-Y-Rita, P. (2006). Tactile sensory substitution studies. *Annals of the New York Academy of Sciences*, *1013*(1), 83–91. https://doi.org/10.1196/annals.1305.006

[3] Basdogan, C., Giraud, F., Levesque, V., & Choi, S. (2020). A review of surface haptics:Enabling tactile effects on touch surfaces. In *arXiv [cs.HC]*. http://arxiv.org/abs/2004.13864

[4] Bertram, C., Evans, M. H., Javaid, M., Stafford, T., & Prescott, T. (2013). Sensory augmentation with distal touch: The tactile helmet project. In *Biomimetic and Biohybrid Systems* (pp. 24–35). Springer Berlin Heidelberg.

[5] Bharadwaj, A., Shaw, S. B., & Goldreich, D. (2019). Comparing tactile to auditory guidance for blind individuals”. *Frontiers in Human Neuroscience*, *13*.

[6] Bliss, J., Katcher, M., Rogers, C., & Shepard, R. (1970). Optical-to-tactile image conversion for the blind. *IEEE Transactions on Man Machine Systems*, *11*(1), 58–65. https://doi.org/10.1109/tmms.1970.299963

[7] Boles, D. B., & Givens, S. M. (2011). Laterality and sex differences in tactile detection and two-point thresholds modified by body surface area and body fat ratio. *Somatosensory & Motor Research*, *28*(3–4), 102–109. https://doi.org/10.3109/08990220.2011.627068

[8] Borg, B. (2020, December 17). The 3 categories of performance testing metrics you need to measure. *Onpathtesting.Com*. https://www.onpathtesting.com/blog/performance-testing-metrics

[9] Bourne, R., Steinmetz, J. D., Flaxman, S., Briant, P. S., Taylor, H. R., Resnikoff, S., Casson, R. J., Abdoli, A., Abu-Gharbieh, E., Afshin, A., Ahmadieh, H., Akalu, Y., Alamneh, A. A., Alemayehu, W., Alfaar, A. S., Alipour, V., Anbesu, E. W., Androudi, S., Arabloo, J., … Vos, T. (2021). Trends in prevalence of blindness and distance and near vision impairment over 30 years: an analysis for the Global Burden of Disease Study. *The Lancet. Global Health*, *9*(2), e130–e143. https://doi.org/10.1016/s2214-109x(20)30425-3

[10] *BrainPort for the blind*. (n.d.). Asme.Org. Retrieved February 4, 2022, from https://www.asme.org/topics-resources/content/brainport-for-the-blind.

[11] Brown, F. E., Sutton, J., Yuen, H. M., Green, D., Van Dorn, S., Braun, T., Cree, A. J., Russell, S. R., & Lotery, A. J. (2019). A novel, wearable, electronic visual aid to assist those with reduced peripheral vision. *PloS One*, *14*(10), e0223755. https://doi.org/10.1371/journal.pone.0223755

[12] Cassinelli, A., Reynolds, C., & Ishikawa, M. (2006). Augmenting spatial awareness with Haptic Radar. *2006 10th IEEE International Symposium on Wearable Computers*.

[13] Christine, B. (1993). Facial sensibility in patients with unilateral facial nerve paresis. *Otholaryngology-Head and Neck Surgery*, *109*, 506–513.

[14] Clark, R. N. (n.d.). *Clarkvision photography - resolution of the human eye*. Clarkvision.Com. Retrieved April 21, 2022, from https://clarkvision.com/imagedetail/eye-resolution.html

[15] *Coin LRA vibration motors*. (n.d.). Vybronics. Retrieved March 9, 2022, from https://www.vybronics.com/products/coin-vibration-motors/lra

[16] Collins, C. (1970). Tactile television mechanical and electrical image projection. *IEEE Transactions on Man Machine Systems*, *11*(1), 65–71. https://doi.org/10.1109/tmms.1970.299964

[17] *ERM brush type coin vibration motors*. (n.d.). Vybronics. Retrieved March 9, 2022, from https://www.vybronics.com/products/coin-vibration-motors/with-brushes

[18] *Everything you need to know about haptic technology*. (n.d.). D-BOX. Retrieved June 1, 2022, from https://www.d-box.com/en/haptic-technology

[19] Giudice, N. A., Guenther, B. A., Kaplan, T. M., Anderson, S. M., Knuesel, R. J., & Cioffi, J. F. (2020). Use of an indoor navigation system by sighted and blind travelers: Performance similarities across visual status and age. *ACM Transactions on Accessible Computing*, *13*(3), 1–27. https://doi.org/10.1145/3407191

[20] Goldish, L. H., & Taylor, H. E. (1974). The Optacon: A valuable device for blind persons. *Journal of Visual Impairment & Blindness*, *68*(2), 49–56. https://doi.org/10.1177/0145482x7406800201

[21] González-Cañete, F. J., López Rodríguez, J. L., Galdón, P. M., & Díaz-Estrella, A. (2019). Improvements in the learnability of smartphone haptic interfaces for visually impaired users. *PloS One*, *14*(11), e0225053. https://doi.org/10.1371/journal.pone.0225053

[22] Gori, M., Cappagli, G., Tonelli, A., Baud-Bovy, G., & Finocchietti, S. (2016). Devices for visually impaired people: High technological devices with low user acceptance and no adaptability for children. *Neuroscience and Biobehavioral Reviews*, *69*, 79–88. https://doi.org/10.1016/j.neubiorev.2016.06.043

[23] Greene, M. (n.d.). *Haptic Feedback Technology*. Msu.Edu. Retrieved March 17, 2022, from https://www.egr.msu.edu/classes/ece480/capstone/fall14/group04/assets/appnote_michael.pdf

[24] *Guide to Haptic actuators in product design – Haptic feedback actuators*. (2021, November 7). Engineering Product Design. https://engineeringproductdesign.com/knowledge-base/haptic-actuators/

[25] *Hikayemiz*. (2021, March 15). WeWALK Smart Cane. https://wewalk.io/tr/hakkimizda/

[26] *IndoorNavGuide*. (2021, April 15). SightCity Frankfurt 2021 FTS-Project. https://fts.vgtu.lt/sightcity-frankfurt-2021/

[27] Jain, D., Agrawal, P., Maheshwari, K., Mittal, A., Gupta, A., Ollagnier, A., Goyal, A., Paul, R., Ranjan, A., Gupta, A., Paldhe, M., Das, S., Sanyal, S., Taneja, Y., & Manocha, D. (n.d.). *Design and user testing of an affordable cell-phone based indoor navigation system for visually impaired*. Washington.Edu. Retrieved June 2, 2022, from https://homes.cs.washington.edu/~djain/img/portfolio/Jain_Roshni_TRANSED2012.pdf

[28] Jones, L. A., Lockyer, B., & Piateski, E. (2006). Tactile display and vibrotactile pattern recognition on the torso. *Advanced Robotics*, *20*(12), 1359–1374.

[29] Kaczmarek, K. A. (2011). The tongue display unit (TDU) for electrotactile spatiotemporal pattern presentation. *Scientia Iranica. Transactions D, Computer Science & Engineering, Electrical Engineering*, *18*(6), 1476–1485. https://doi.org/10.1016/j.scient.2011.08.020

[30] Kaczmarek, Kurt A., & Bach-Y-Rita, P. (1995). Tactile Displays. In *Virtual Environments and Advanced Interface Design*. Oxford University Press.

[31] Kajimoto, H. (2006). *Forehead electro-tactile display for vision substitution*. https://www.semanticscholar.org/paper/4d61efe8fd515c55fb6f8c3f5c5bf8d48cffc2b4

[32] Khurelbaatar, S., Nakai, Y., Okazaki, R., Yem, V., & Kajimoto, H. (2016). Tactile presentation to the back of a smartphone with simultaneous screen operation. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*.

[33] Koskinen, S., & Virtanen, A. (n.d.). *Navigation system for the visually impaired based on an information server concept*. Vtt.Fi. Retrieved June 1, 2022, from http://virtual.vtt.fi/virtual/noppa/mvenue/navigationsystemforthevisuallyimpairedbasedonaninformation.pdf

[34] Kristjánsson, Á., Moldoveanu, A., Jóhannesson, Ó. I., Balan, O., Spagnol, S., Valgeirsdóttir, V. V., & Unnthorsson, R. (2016). Designing sensory-substitution devices: Principles, pitfalls and potential1. *Restorative Neurology and Neuroscience*, *34*(5), 769–787. https://doi.org/10.3233/RNN-160647

[35] Lindeman, R. W., & Yanagida, Y. (2003). Empirical studies for effective near-field haptics in virtual environments. *IEEE Virtual Reality, 2003. Proceedings*.

[36] McDaniel, T., Krishna, S., Balasubramanian, V., Colbry, D., & Panchanathan, S. (2008). Using a haptic belt to convey non-verbal communication cues during social interactions to individuals who are blind. *2008 IEEE International Workshop on Haptic Audio Visual Environments and Games*.

[37] *Mini PowerHap actuators for haptic feedback*. (n.d.). TDK Electronics AG. Retrieved March 9, 2022, from https://www.tdk-electronics.tdk.com/en/374108/tech-library/articles/products-technologies/products-technologies/mini-powerhap-actuators-for-haptic-feedback/2517756

[38] *Natural Sense of Acoustics and Haptics*. (n.d.). Europa.Eu. Retrieved March 3, 2022, from https://cordis.europa.eu/project/id/643636

[39] Neugebauer, A., Rifai, K., Getzlaff, M., & Wahl, S. (2020). Navigation aid for blind persons by visual-to-auditory sensory substitution: A pilot study. *PloS One*, *15*(8), e0237344. https://doi.org/10.1371/journal.pone.0237344

[40] Ozgonul, C. (2021). *Görme Engelliler İçin Yapay Zeka Destekli Yapay Görme Sistemi*. Tıp Fakültesi.

[41] Petri Pulli, B. C. (2014). Smart cane outdoor navigation system for visually impaired deaf-blind and blind persons. *Journal of Communication Disorders Deaf Studies & Hearing Aids*, *02*(04). https://doi.org/10.4172/2375-4427.1000125

[42] *PowerHapTM Piezo Actuators*. (n.d.). Mouser. Retrieved March 10, 2022, from https://www.mouser.com.tr/c/?marcom=138108910

[43] Ptito, M., Bleau, M., Djerourou, I., Paré, S., Schneider, F. C., & Chebat, D.-R. (2021). Brain-machine interfaces to assist the blind. *Frontiers in Human Neuroscience*, *15*, 638887. https://doi.org/10.3389/fnhum.2021.638887

[44] Quadri, S. M. K. (2017). *Software measurements and metrics: Role in effective software testing*. https://www.academia.edu/32263033/Software_Measurements_and_Metrics_Role_in_Effective_Software_Testing

[45] Renier L, & De Volder, A. G. (2013). *Sensory Substitution Devices*. Oxfordhandbooks.Com. https://doi.org/10.1093/oxfordhb/9780199603329.013.0042.

[46] Sato, T., Okada, Y., Miyamoto, T., & Fujiyama, R. (1999). Distributions of sensory spots in the hand and two-point discrimination thresholds in the hand, face and mouth in dental students. *Journal of Physiology, Paris*, *93*(3), 245–250. https://doi.org/10.1016/s0928-4257(99)80158-2

[47] Segond, H., Weiss, D., & Sampaio, E. (2005). Human spatial navigation via a visuo-tactile sensory substitution system. *Perception*, *34*(10), 1231–1249. https://doi.org/10.1068/p3409

[48] Seim, C. E., Wolf, S. L., & Starner, T. E. (2021). Wearable vibrotactile stimulation for upper extremity rehabilitation in chronic stroke: clinical feasibility trial using the VTS Glove. *Journal of Neuroengineering and Rehabilitation*, *18*(1), 14. https://doi.org/10.1186/s12984-021-00813-7

[49] Seim, C., Hallam, J., Raghu, S., Le, T.-A., Bishop, G., & Starner, T. (n.d.). *Perception in hand-worn haptics: Placement, simultaneous stimuli, and vibration motor comparisons*. Gatech.Edu. Retrieved June 1, 2022, from https://smartech.gatech.edu/bitstream/handle/1853/55952/SeimTechReport16Steno.pdf

[50] Sirinturk, S., Bagheri, H., Govsa, F., Pinar, Y., & Ozer, M. A. (2017). Study of frontal hairline patterns for natural design and restoration. *Surgical and Radiologic Anatomy: SRA*, *39*(6), 679–684. https://doi.org/10.1007/s00276-016-1771-1

[51] *Smart Cane*. (2021, March 15). WeWALK Smart Cane. Retrieved March 2, 2022, from https://wewalk.io/tr/urun/

[52] Stiles, N. R. B., & Shimojo, S. (2015). Auditory sensory substitution is intuitive and automatic with texture stimuli. *Scientific Reports*, *5*(1), 15628. https://doi.org/10.1038/srep15628

[53] Van Erp, J. (2005). Presenting directions with a vibrotactile torso display. *Ergonomics*, *48*(3), 302–313. https://doi.org/10.1080/0014013042000327670

[54] Velázquez, R. (2010). Wearable assistive devices for the blind. In *Wearable and Autonomous Biomedical Devices and Systems for Smart Environment* (pp. 331–349). Springer Berlin Heidelberg.

[55] *VIBRATION LRA MOTOR*. (n.d.). Digikey. Retrieved March 10, 2022, from https://www.digikey.com/en/products/detail/vybronics-inc/VG0825001D/10285885

[56] *Vibration motors*. (2021, July 1). Precision Microdrives. . Retrieved March 10, 2022, from https://www.precisionmicrodrives.com/motors/vibration-motors

[57] White, B. W., Saunders, F. A., Scadden, L., Bach-Y-Rita, P., & Collins, C. C. (1970). Seeing with the skin. *Perception & Psychophysics*, *7*(1), 23–27. https://doi.org/10.3758/bf03210126

[58] Won, S.-Y., Kim, H.-K., Kim, M.-E., & Kim, K.-S. (2017). Two-point discrimination values vary depending on test site, sex and test modality in the orofacial region: a preliminary study. *Journal of Applied Oral Science*, *25*(4), 427–435. https://doi.org/10.1590/1678-7757-2016-0462

[59] Yang, T.-H., Kim, J. R., Jin, H., Gil, H., Koo, J.-H., & Kim, H. J. (2021). Recent advances and opportunities of active materials for haptic technologies in virtual and augmented reality. *Advanced Functional Materials*, *31*(39), 2008831. https://doi.org/10.1002/adfm.202008831

[60] Yizhar, O., Buchs, G., Heimler, B., Friedman, D., & Amedi, A. (2021). Applying a novel visual-to-touch sensory substitution for studying tactile reference frames. *Scientific Reports*, *11*(1), 10636. https://doi.org/10.1038/s41598-021-90132-7

[61] Khan, I., Khusro, S., & Ullah, I. (2018). Technology-assisted white cane: evaluation and future directions. *PeerJ*, *6*(e6058), e6058. https://doi.org/10.7717/peerj.6058

[62] dos Santos, A. D. P., Medola, F. O., Cinelli, M. J., Garcia Ramirez, A. R., & Sandnes, F. E. (2021). Are electronic white canes better than traditional canes? A comparative study with blind and blindfolded participants. *Universal Access in the Information Society*, *20*(1), 93–103. https://doi.org/10.1007/s10209-020-00712-z

[63] Zhang, P. (2010). Sensors and actuators. In P. Zhang (Ed.), *Advanced Industrial Control Technology* (pp. 73–116). Elsevier

[64] Shafik, A., & Ben Mrad, R. (2016). Piezoelectric Motor Technology: A Review. In *Nanopositioning Technologies* (pp. 33–59). Springer International Publishing.

[65] Crowder, R. (2020). Related motors and actuators. In R. Crowder (Ed.), *Electric Drives and Electromechanical Systems* (pp. 227–239). Elsevier.

[66] *Sensory Acuity*. Teachmephysiology.com. Retrieved December 8, 2023, from https://teachmephysiology.com/nervous-system/sensory-system/sensory-acuity

[67] Tazehkandi, A. A. (2018). *Computer vision with OpenCV 3 and Qt5: Build visually appealing, multithreaded, cross-platform computer vision applications*. Packt Publishing.

[68] Feng, J., Liu, P., & Kim, Y. K. (2022). Foreground detection based on superpixel and semantic segmentation. *Computational Intelligence and Neuroscience*, *2022*, 1–14. https://doi.org/10.1155/2022/4331351.

[69] Koara, K., Nishikawa, A., & Miyazaki, F. (2001). Contour based hierarchical part decomposition method for human body motion analysis from video sequence. In E. Arai, T. Arai, & M. Takano (Eds.), *Human Friendly Mechatronics* (pp. 235–240). Elsevier.

[70] Ashir, A. M. (2022). Multilevel thresholding for image segmentation using mean gradient. Journal of Electrical and Computer Engineering, 2022, 1–9. https://doi.org/10.1155/2022/1254852

[71] Yan, F., Zhang, H., & Kube, C. R. (2005). A multistage adaptive thresholding method. *Pattern Recognition Letters*, *26*(8), 1183–1191. https://doi.org/10.1016/j.patrec.2004.11.003

[72] Samantaa, S., Dey, N., Das, P., Acharjee, S., & Chaudhuri, S. S. (2013). *Multilevel threshold based gray scale image segmentation using Cuckoo Search*. https://doi.org/10.48550/ARXIV.1307.0277

[73] Buhl, N. (2023, September 12). *Image thresholding in image processing*. Encord.com; Encord Blog. https://encord.com/blog/image-thresholding-image-processing

[74] Bradley, D., & Roth, G. (2007). Adaptive Thresholding using the Integral Image. *Journal of Graphics Tools*, *12*(2), 13–21. https://doi.org/10.1080/2151237x.2007.10129236

[75] Rosebrock, A. (2021, May 12). *Adaptive thresholding with OpenCV (cv2.adaptiveThreshold)*. PyImageSearch. https://pyimagesearch.com/2021/05/12/adaptive-thresholding-with-opencv-cv2-adaptivethreshold/

[76] Fisher, R., Perkins, S., Walker, A., & Wolfart, E. (2003). *Gaussian Smoothing*. Ed.ac.uk. https://homepages.inf.ed.ac.uk/rbf/HIPR2/gsmooth.htm

[77] Nixon, M., & Aguado, A. (n.d.). *Gaussian Filtering*. Southampton.ac.uk. Retrieved March 20, 2024, from https://www.southampton.ac.uk/~msn/book/new_demo/gaussian/

[78] Donald Danforth Plant Science Center. (2020). *Gaussian adaptive threshold*. Readthedocs.Io. https://plantcv.readthedocs.io/en/stable/gaussian_threshold/

[79] *OpenCV: Image Thresholding*. Opencv.org. Retrieved March 25, 2024, from https://docs.opencv.org/4.x/d7/d4d/tutorial_py_thresholding.html

[80] *Understanding Otsu's Method for Image Segmentation*. (2023, May 6). Baeldung.com. https://www.baeldung.com/cs/otsu-segmentation

[81] Otsu, N. (1979). A threshold selection method from gray-level histograms. *IEEE Transactions on Systems, Man, and Cybernetics*, *9*(1), 62–66. https://doi.org/10.1109/tsmc.1979.4310076

[82] Li, N., Lv, X., Xu, S., Li, B., & Gu, Y. (2020). An improved water surface images segmentation algorithm based on the Otsu method. *Journal of Circuits Systems and Computers*, *29*(15), 2050251. https://doi.org/10.1142/s0218126620502515

[83] Bangare, S. L., Dubal, A., Bangare, P. S., & Patil, S. T. (2015). Reviewing Otsu's Method For Image Thresholding. *International Journal of Applied Engineering Research*, *10*(9), 21777–21783. https://doi.org/10.37622/ijaer/10.9.2015.21777-21783

[84] Bindu, H., & Satya Prasad, K. (2012). An Efficient Medical Image Segmentation Using Conventional OTSU Method. *International Journal of Advanced Science and Technology*, *38*, 67–73. https://www.researchgate.net/publication/267723666_An_Efficient_Medical_Image_Segmentation_Using_Conventional_OTSU_Method

[85] Srikanth, R., & Bikshalu, K. (2021). Multilevel thresholding image segmentation based on energy curve with harmony Search Algorithm. *Ain Shams Engineering Journal*, *12*(1), 1–20. https://doi.org/10.1016/j.asej.2020.09.003

[86] *Multi-Otsu Thresholding — skimage 0.22.0 documentation*. Scikit-image.org. Retrieved February 12, 2024, from https://scikit-image.org/docs/stable/auto_examples/segmentation/plot_multiotsu.html

8 CURRICULUM VITAE