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**Parameter optimization and system miniaturization for
vibrotactile information transfer**

Perez, Claudio Andres, Ph.D.

The Ohio State University, 1991

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PARAMETER OPTIMIZATION AND SYSTEM
MINIATURIZATION FOR VIBROTACTILE INFORMATION
TRANSFER

A Dissertation

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the
Graduate School of the Ohio State University

by

Claudio A. Perez, B.S., P.E., M.S.

* * * * *

The Ohio State University

1991

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A handwritten signature in dark ink, appearing to read 'Herman R. Weed', is written over a horizontal line.

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To my wife, Patricia, and my children

Claudio I., Patricia A. and Andres P.

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CHAPTER I

INTRODUCTION

1.1 Background of the Problem

Although transferring visual information to visually handicapped individuals through the tactile sense has been a possibility since the late 1960's, today there is still no commercial instrument available to transfer this information. Many devices have been built but unfortunately the problems of size, versatility and power consumption have prevented their practical application [1, 2].

The controlled application of mechanical stimulation to the skin using vibrators is a means of transferring information to individuals using other than the traditional visual and auditory channels. The skin as an information transferring channel has been used for visually and hearing handicapped individuals and in situations where it is desirable to transfer additional information to an individual while he/she is using the visual and auditory senses for other purposes, e.g., aircraft pilots.

Temporal and spatial parameters involved in the application of mechanical stimulation to the skin are closely related to the sensation and shape recognition thresholds. In addition it is desirable to transfer information as fast as possible with minimum power to provide real time access to visual information and to achieve portability of the system, i.e., miniaturization of the hardware and power supply. Therefore, the pattern of stimulation must be optimized temporally and spatially to produce the best sensation and recognition thresholds, maximizing the rate of information

transfer and minimizing the power consumed.

The relevant temporal parameters of the vibrator driving waveform involved in the mechanical stimulation of the skin are: amplitude and frequency of stimulation, and if a pulse, pulse width, number of pulses per burst and recovery time. The latter is necessary to recover from the adaptation of the mechanoreceptors of the skin to the stimulation. The most relevant spatial parameter is the maximum spatial resolution of the skin surface, which determines the maximum number of stimulators per unit area of the skin.

National projections [3] indicate that more than 3 million persons are visually impaired (vision $\leq 20/60$) and that 890,000 of those are blind by US definitions (vision $\leq 20/400$). The primary causes of blindness in children include malnutrition, infectious diseases and injury. Among the most common diseases causing blindness are German measles during the first few months of pregnancy of the mother, glaucoma, diabetic retinopathy, senile cataracts and senile retinal degeneration. More than 30% of the new cases of blindness occur in persons over 65 years old [4].

A system to provide real time visual information transfer to visually handicapped individuals would have a definite impact on their lives. It would provide insight into the environment, remote primitive object identification, and stress relief when performing tasks involving mobility, orientation or object handling. These factors would improve the quality of life, the job performance, and self-confidence of these population.

1.2 Objective of the Research

The objectives of this research were to investigate, design and develop an improved, low cost, potentially-portable, experimental system which was capable of

transferring optical images into tactile pictures to aid the visually handicapped, and to optimize the relationship of the parameters of the driving waveform used to excite the electro-mechanical transducers, relative to skin sensitivity and power delivered to the vibrator.

This research addressed two areas:

The first area of the investigation was the design and implementation of a research prototype system which reduced significantly the size and power requirements of the system compared to previous attempts, and to provide the capability of testing the various combinations of parameters of the driving waveform, and the different modes of presentation of the visual information to the handicapped.

The second area of research was the identification ¹ and investigation of the basic parameters of the driving waveform to optimize their relationship relative to skin sensitivity and power delivered by the driving waveform.

Results from the first area of the research provide a first prototype from which miniaturization towards portability appears possible. This research prototype has the testing capability to vary the significant parameters so as to evaluate the response of the skin to mechanical stimuli being optimized for sensitivity and power. It also provides a research tool for future investigations on the effect of image processing enhancements and on modes of presenting a tactile information on the vibratory array.

Results from the second area of the research make it possible to specify the optimal combination of parameters of the driving waveform such as amplitude, frequency, pulse shape, number of pulses per burst, duty cycle and recovery time to produce a

¹Most of the significant parameter identification had been done in previous work.

compromise between maximum rate of information transfer with maximum sensitivity and minimum power consumption.

1.3 Organization of the Dissertation

The remainder of the dissertation consists of four chapters. Chapter II presents the background and definitions for the work. The selection of the tactile approach for information transfer is examined and the characteristics of the skin receptors relevant to mechanical stimulation are introduced. Then, the choice of transducer, its driving waveform, and sensitivity of the skin are discussed. This leads to the development of the motivation for the present study.

Chapter III considers the design and development of the experimental electronic system to transfer optical images into tactile pictures. The specifications of the system, including the design for research needs, are given, followed by the circuit design for the size reduction strategy. The rationale for the selected design and the system's main block diagrams are given, and the system's operation is discussed. This is followed by a discussion of the timing considerations, the main software modules, and the results at the end of the chapter.

In Chapter IV is presented the theoretical and experimental investigation of the critical parameters of the transducer's driving waveform, relative to skin sensitivity and power delivered, including the theoretical analysis of the driving waveform and its spectral analysis. This is followed by a theoretical section on the power delivered within the window of frequencies where the mechanoreceptors are sensitive. From the power within this window the pulse amplitudes needed to reach sensation are predicted. The justification for the experimental part of the research, the experimental design, the experimental methods, and the results are detailed. The total power

delivered by the driving waveform as a function of the parameters, pulse frequency and pulse width, are calculated in order to make it possible to select the combination of parameters that maximize sensitivity while minimizing power delivered. The theoretical predictions and the experimental results are contrasted.

Chapter V covers the conclusions and future research.

CHAPTER II

BACKGROUND, DEFINITIONS AND THEORY

2.1 Selection of the Tactile Approach for Information Transfer

Three main areas of research are involved in designing a system intended to substitute the eye to aid the visually handicapped. These are: (a) image acquisition, which involves the gathering of information about the environment, (b) information processing to manipulate the data so that it can be interfaced with (c), and (c) a man-machine interface which performs the transduction of information from the processed data to match the characteristics of the sensory system selected to receive it.

In each of these three areas there are choices to be made. In image acquisition several means are available for gathering information about the environment. Sound can be used to scan and acquire information about the environment by receiving back the reflections of the sound waves from objects. Electromagnetic waves such as radar can also be used to scan the environment and receive reflections back from objects. In this research an optical sensor was selected because it closely resembles information provided by normal vision and because it does not require the emission of additional energy into the environment [5].

The information processing device chosen was a computer because of its flexibility in generating the tests for various parameters and the special image processing capabilities needed for the research. Processing capabilities include edge enhancement,

invert/normal mode, various averaging techniques, and various modes of presenting the information to the selected sensory system.

There are five major human sensory channels that could be used in the man-machine interface to transfer information to an individual: sight, hearing, tactile, taste and smell. Sight can be ruled out because it is the sense being replaced. Hearing is ruled out because it is a sense that is continually being used to gather information about the environment and to communicate with other people and therefore it is not desirable to obstruct it. Taste and smell can be discarded because of the slow speed of response, not suitable to transfer visual information in real time. The variety of skin sensors gives the choice of using electrical current, pressure, heat, or vibration as stimuli. An added advantage of using the skin as a channel for visual information transfer is that a one-to-one mapping from the surface of the skin to the somatosensory cortex of the central nervous system is supplied naturally by the neuro-anatomy of the human. This fact reduces the learning process in associating external spatial distributions of stimulus sources with specific sensations. Finally, the use of the tactile sense to transfer information constitutes a non-invasive, hazard free approach compared to other possible approaches, such as electrical stimulation of the skin.

Electrical stimulation of the skin presents two major problems. The first is that the threshold for sensation is close to that of pain and is variable so that it is difficult to adjust to the right level. The second is that for an array of more than 200 electrodes, for a medium resolution prosthesis, it is difficult to maintain good contact in all of the electrodes and when the area of contact decreases, the current density increases, resulting in pain or burns on the tissue. Pressure transducers were ruled out because they were considered bulky and the pressure receptors adapt quickly to

pressure [5, 6]. Heat sensors were also considered unsuitable because of their slow response to stimuli and their poor spatial discrimination. The mechanoreceptors of the skin respond well to stimuli at frequencies of about 250 Hz (± 100 Hz). Their spatial resolution varies substantially from one location of the body to another. For example, the two point discrimination on the index finger is 2.5 mm, while that on the trunk is around 68 mm. Nevertheless, high resolution displays placed on the back, with spacings of only 12 mm, have been shown not to be redundant [2]. Therefore, the mechanoreceptors seem to be appropriate for real time information transfer.

2.2 The Skin as Sensory Input Channel

The skin supplies a major path for sensory input to the central nervous system providing information about the environment. The skin has a variety of receptors that enable humans to identify cutaneous sensations such as: touch, pressure, warmth, cold and pain. There are at least 15 functionally and morphologically distinct afferent units. The afferent input from these units is the raw material from which cutaneous sensations are derived. The exact correlation between tactile sensation and each of the afferent inputs has not yet been determined because it is not possible to restrict the sensory input to cause activation of only a single type of nerve fiber. Different mechanoreceptors may contribute in varying degrees to produce a particular sensation [7, 8]. Even though sensations depend on an input from afferent units (receptors) from the skin, the central nervous system can modify the messages ascending to the higher levels of the brain, shaping the sensations that are actually experienced.

The sensory acuity of the skin varies over different regions of the body. These differences are attributable to the different densities of sensory innervation, the dif-

ferent receptive field size which the afferent sensory unit innervates, and the various kinds of receptors present in the skin in different parts of the body. For example, the fingertips are densely innervated compared to the back, and their receptors for mechanical deformation are very sensitive, thus providing a wider range of spatial and intensity information about the tactile stimulus in contrast to other regions of the body.

The sensory input through the skin is performed by receptors that can be classified in three categories. Mechanoreceptors which are sensitive to mechanical stimulation, thermoreceptors which are sensitive to temperature gradients, and nociceptors which are the "pain" receptors that are sensitive to potentially damaging or very intense stimuli.

Since for the present research the selected approach to the transfer of optical information to the visually handicapped was through the tactile system, the rest of the discussion on skin receptors will focus on the mechanoreceptors.

2.3 Characteristics of the Mechanoreceptors of the Skin

The mechanoreceptors of the skin are highly sensitive and reasonably specific to mechanical deformation of the skin or to hair movement. The mechanoreceptors can be classified into two kinds, rapidly adapting and slowly adapting [7]. Figure 1 shows a magnified section of the skin, showing its different layers and mechanoreceptors.

2.3.1 Rapidly Adapting Mechanoreceptors

The rapidly adapting (RA) mechanoreceptors code velocity of movement as a frequency of discharge. Three types of receptors are included in the RA group:

Figure 1: Magnified section of the skin showing different layers and mechanical receptors. From Mountcastle, 1980.

Pacinian corpuscles (PC), Meissner's corpuscles and hair follicle receptors. See Figure 1 for relative location and shape [9].

The PC is 0.5 to 2 mm long, with an onion-like shape and lamellar structure. It lies in the deeper skin layers and its afferent fiber is myelinated. Its most outstanding characteristic is its sensitivity to mechanical vibration at high frequencies in the range 200-400 Hz. The receptor will respond over a range 70 - 1000 Hz, but requires stronger stimuli toward the high and low frequency ends. Below 50 Hz it does not respond to mechanical stimulation. The PC is very specific to mechanical stimulation and will not respond to changes in temperature.

The Meissner's corpuscle is an encapsulated receptor with a myelinated afferent fiber. It lies in the dermis of human glabrous (hairless) skin. Its effective frequency range for stimulus detection is lower than that for the PC and is between 10 - 200 Hz.

The third type of RA mechanoreceptor is the hair follicle which is innervated by a myelinated afferent fiber. The fibers discharge impulses only when the hair is moved. They play the same role for hairy skin as the Meissner's corpuscle in glabrous skin.

2.3.2 Slowly Adapting Mechanoreceptors

Slowly adapting mechanoreceptors respond to displacements of the skin rather than velocity of motion, and they sustain the discharge of impulses when the stimulus is constant. During the plateau of the stimulus the rate of firing decreases, reaching a rate proportional to the amount of indentation. This rate is particular to the kind of SA mechanoreceptor and to the tissue in which the receptor lies. Two kinds of SA mechanoreceptors have been described, the SA-I and the SA-II. They differ mainly

in the time constants of adaptation; the SA-I adapt more quickly than the SA-II. Figure 1 shows these receptors.

The SA-I are Merkel cells located at the base of the epidermis. They are normally silent when no mechanical stimulus is applied. The response they provide can be an irregular stream of pulses.

The SA-II mechanoreceptors are Ruffini endings located in the dermis of hairy and glabrous skin, frequently lying more deeply than the Meissner's corpuscle. They are able to provide continuous output in response to steady pressure within the skin.

2.3.3 Receptor Adaptation/Recovery Time

Adaptation is the reduced response of a receptor to a stimulus above threshold following exposure to a continued excitation above threshold. The recovery time is the time that a receptor takes after it has been subjected to excitation above threshold to respond again with its normal sensitivity. One possible mechanism of such adaptation is depletion of the neuro-transmitters by the continuous stimulation [10, 5].

2.3.4 Frequency Response of Mechanoreceptors

The cutaneous mechanoreceptors provide an overall response to stimuli of different frequencies shown in Figure 2. This figure shows the displacement required to produce sensation threshold versus the frequency of the sinusoidal stimulus. Three curves are presented; for the psychophysical response, the PCs, and the dermal ridge receptors. It can be observed that in the psychophysical response curve there is a region around 250 Hz where the sensitivity of the skin is maximum. Studies have shown that the upper and lower ends of this frequency range are provided by different kinds

of mechanoreceptors as Figure 2 shows. In the case of the RA mechanoreceptors, the Meissner's corpuscle (glabrous skin) and hair follicle (hairy), correspond closely in their thresholds to the human sensation thresholds at the lower frequencies and the PC thresholds match them at the higher frequencies. There is also evidence that there are areas of the somatosensory cortex that respond selectively to sinusoidal cutaneous stimulation in the ranges 5-80 Hz, 80-400 Hz, or to constant stimulus.

2.4 Transducers

Several different types of transducers have been used in past research. Piezoelectric transducers were used in the Optacon but required addition of a leverage system to produce adequate displacements [11, 12]. Kovach [12] showed that in order to produce an adequate stimulus for the tactile sense, i.e., a displacement of $200\ \mu m$ with a force of 30 mN and a safe maximum applied voltage of 20 v, the diameter of a piezoelectric ceramic disc would have to be at least 3.49 cm. This diameter is not appropriate for visual information transfer through the tactile sense because in order to have a minimum usable resolution of around 200 transducers, for that diameter of transducer an area of skin of about $50 \times 50\ cm^2$ would be required. Similarly, for piezoelectric ceramic bimorphs Kovach [12] calculated that the minimum width required to produce an adequate tactile stimulus was 1.59 cm. Additional considerations, such as the brittle nature of ceramic bimorphs and their stiffness, make it difficult to protect them and maintain good contact with the skin for a reasonable length of time. Thus, it was considered that it would be very difficult to assemble a durable, portable array of ceramic bimorphs. Piezoelectric film was also considered [12]; and the minimum length to produce the adequate stimulus for the tactile sense was determined to be 21.5 cm, making it the least useful of the three piezoelectric

Figure 2: Tactile Sensation Thresholds. From Rogers, 1970.

transducers reviewed.

Solenoids have been used successfully in early systems [11] but in general are larger, heavier and more expensive than miniature audio transducers. Kovach [12] determined that in order to produce a detectable stimulus with pulses of 0.3125 ms at 200 Hz, the average power level required was 5 W per transducer. This is very high considering that the tactile array will be composed of a few hundred transducers, and is not compatible with building a portable system.

In Kovach [12] a miniature audio transducer, the QMB-105 from Star Micronics, was selected as the electrical-to-mechanical transducer because of its relatively small size of 1.1 cm diameter, its low weight of 2 g, and its low cost of \$0.50 each. The mechanical motion is produced by vibration of a stainless steel plate of 50 μm thickness. A carbon steel disc, as shown in Figure 3, of approximately 4 mm diameter is attached at the center of the plate to improve permeability to magnetic flux [11]. This disc, which is recessed approximately 0.14 mm below a surrounding plastic case, served also as the area contacting the skin. These transducers were able to produce a detectable stimulus on the abdomen with 20 mW of applied power at a frequency of 200 Hz [12]. Thus, the QMB-105 transducer was chosen as the man-machine interface for this research because it had the best characteristics among all the transducers evaluated for the tactile information transfer system.

2.5 Choice of Location for Array

One of the goals of this research is to design the system to transfer visual information so that it is non-obstructive to the extremities, allowing mobility and free movement of the hands for the user. In addition, since the system is designed to transfer visual information, the larger the number of transducers, the higher the res-

Figure 3: QMB-105 miniature audio transducer showing body dimensions in mm.
From Kovach, 1985.

olution. Unfortunately, the larger the number of transducers, the larger the array's size, weight and power requirements, making it less desirable for use as a portable device. There are three areas of the body providing a relatively large surface area of skin of 20 cm by 20 cm: the abdomen, the thigh or the back. Given the size of the QMB-105 transducer selected for this research (see section 2.4), a tactile array of 16x16 transducers can be accommodated within the 20 cm by 20 cm area of skin. Although the sensitivity of these regions to vibrotactile stimulation is similar [13], the back has a lower density of innervation and its sensation thresholds are the highest of the three.

2.6 Sensitivity

In the experimental part of this research, sensitivity of the skin response to a vibratory stimulus is defined as the inverse of the peak current pulse through the vibrator necessary to produce sensation.

2.7 Transducer Excitation Waveform: The Stimulatory Waveform

The pattern of stimulation applied to the transducers controls the resulting mechanical displacement. Therefore the pattern of stimulation must be tuned to obtain the best psychophysical response from the interface transducer/mechanoreceptor/sensation. From the frequency response curve for the mechanoreceptors in Figure 2, it can be observed that the receptors are most sensitive to sinusoidal excitation of frequencies around 250 Hz. Therefore, in order to excite a response with minimum stimulus amplitude, i.e., minimum power, a short duty cycle rectangular waveform with a frequency of 250 Hz was chosen [5, 14, 10]. It was determined that reducing the duty cycle to as low as 1/25 caused no significant loss of sensitivity

but achieved a great savings in power delivered [14, 10]. The selection of a 250 Hz rectangular waveform with duty cycle of $1/25$ assumes that the modification in the spectral distribution of the frequency components when changing from a 250 Hz sinusoidal waveform to a 250 Hz rectangular waveform has no influence on the location of the fundamental frequency and pulse width which elicit maximum tactile sensitivity. The hypothesis of the present study is that by changing the spectral distribution of the harmonics of the excitatory waveform, i.e., frequency and pulse width, the optimum frequency for the rectangular waveform will shift from that for the sinusoidal excitation, and therefore the new optimum frequency must be found. This hypothesis will be investigated in Chapter IV, where the parameter optimization part of this research is presented.

Because the tactile sense adapts to a continuous stimulation, to maintain a good level of sensitivity it was necessary to provide a recovery time between periods of stimulation. In previous research [14, 10], several experiments determined that the most suitable recovery time was between 1 and 2 s. Experiments were also performed in previous research to determine the optimum number of pulses in each stimulatory burst. The number of pulses per burst was varied from 1 to 25 [14], with an optimum found around 10 pulses per burst [14, 15, 10]. These optimums determined for the recovery time and for the number of pulses per burst were considered fixed parameters in the present research, since these parameters do not affect the relative spectral distribution of the harmonics of the excitatory waveform. For the development of the experimental system, the recovery time and number of pulses per burst were considered variable to allow future fine tuning adjustments and incorporation of additional variables to the problem under study. Additionally, in previous studies

it was found that first sensation ¹ and line sensation ² thresholds are relatively insensitive to variations around the optimum values of the recovery time and number of pulses per burst. Small variations in these parameters do not affect the sensation threshold significantly. Thus, these parameters could be varied without losing sensitivity, e.g., the recovery time could be shortened from 1 s to 0.8 s to allow increasing the frame rate.

Therefore, the proposed stimulatory waveform was composed of a stimulatory period followed by a recovery time. See Figure 4. The possible variable parameters for the stimulatory waveform are: frequency of stimulation (F), pulse width (W), number of pulses per burst (NPB), recovery time (RT), pulse shape (PS) and pulse amplitude (A). Figure 4 shows the stimulatory waveform, composed of the stimulatory period followed by the recovery time.

2.8 Previous Approaches Using Tactile Stimulation for Information Transfer

The use of vibration applied to the skin for the transfer of visual information is not new. Bach-y-Rita and Collins [16] reported the first attempt by a Polish group in 1898. Bach-y-Rita and Collins built several versions of tactile vision substitution systems at the Smith-Kettlewell Institute of Visual Sciences, and tested them on blind people. The system converted optical images picked up by an electronic camera into vibrational images transferred to the skin through electromechanical vibrators. Only two gray levels were used to transfer the information. The first

¹First sensation is defined as the value of peak current at which the subject just senses the stimulation.

²Line sensation is defined as the value of peak current at which the subject felt the vibrator array as a line touching the skin.

Figure 4: Stimulatory Waveform. The stimulatory period followed by a recovery time (RT) are shown. The stimulatory period is composed of a burst of rectangular pulses of frequency F and pulse width W . Each stimulatory burst is composed of a number of pulses NPB .

complete version weighed more than 400 pounds and was not portable. The image acquisition was done through a television camera mounted on a tripod which was difficult to move and point. The man-machine interface was an array of 20×20 solenoids mounted on the back of a dental chair in which the subject sat. Even with the cumbersome set up of the system, the results were very encouraging. They were able to demonstrate the concept and viability of the approach. Subjects were able to recognize simple objects and perceive spatial relationship between objects. Even congenitally blind subjects with no previous experience in perceptual concepts such as shadows, parallax, looming, and monocular cues for depth were able to learn about them [17]. Subjects reported that the information seemed to originate from in front of the camera rather than from the vibratory array placed on their back [16].

The next step was to make the system portable and usable for the blind commu-

nity. Researchers at the Smith-Kettlewell Institute decided that with the technology available at that time the best way to reduce the size of the system was to change the man-machine interface for one of direct electrical stimulation instead of mechanical stimulation of the skin. After a few versions of systems using electrical stimulation of the skin, the idea was abandoned because of the problems cited in the previous section.

In 1983, research was initiated at the Biomedical Engineering Center of the Ohio State University to develop a state-of-the-art portable system with user feedback and individual user parameter matching. Initial work by Kirschner [5] utilized an approach in which a computer stored and processed a sampled optical pattern picked up by a camera based on a semiconductor optical sensor. The information was then processed to produce a low resolution 16x16 image and transferred to the skin as a vibrating picture. The system was able to produce vibratory pulses in the range of 180-287 Hz with a duty cycle of 1/16 and had the capability of producing variable recovery times from 0.6-2 s. The system provided three different levels of gray and a maximum peak current of 25 mA per vibrator. Previous investigators had used a 250 Hz waveform with fixed pulse duty cycle of 1/2, and a consequently much larger power consumption.

Taige [14] explored the effect of variation in the parameters that characterized the stimulation pattern on the power required to reach sensation. She used a rectangular waveform of 250 Hz and a recovery time of 2 s. She tested sensation thresholds for different number of pulses per burst from one to twenty five, finding the optimum to be between 9 to 12. She also varied the duty cycle from 1/16 to 1/55, finding an optimum for minimum power consumption at a duty cycle of 1/25. It was found that first sensation threshold and discrete touch sensation improved for larger duty

cycles, reaching a more or less flat region for duty cycles above 1/25. Noise produced by the rectangular pulses on the transducer remained a major problem. Nunziata [15] devised a procedure to synthesize band-limited stimulating waveforms whose harmonics remained below a critical threshold for generation of noise. The present system incorporates the results of [14, 15].

2.9 Motivation for the Present Study

There are several critical extensions of previous research that justify the present research.

There has been no success in the past in developing a portable system to transfer visual information to the visually handicapped. The relationships between the parameters of the excitatory waveform and the tactile sensation are not well understood and therefore specific design to minimize size and power consumed by the system has not been possible. Besides, the gap between technology and theoretical realization has been closing in the past years, making available smaller, faster, cheaper devices that will allow reaching the goal of portability and low cost.

M-I Peak Current. Some specific improvements on a previous version of the laboratory system to transfer visual information are necessary to carry out this research. Kirschner's system [5], was designed to produce a maximum peak current of 25 *mA* to the vibrators. This value proved to be barely enough to produce sensation. The new system with the QMB-105 vibrators, must provide a maximum peak current of up to 120 *mA* to assure sensation, not only for the optimum combination of

parameters, but for the various combinations of parameters as required for the investigation of the basic parameters in this research.

M-II Number of Connections. In past research the system was designed so that each individual vibrator had direct wiring to the rest of the electronics, resulting in more than 256 wires between the vibratory array and the rest of the system. This design was clearly incompatible with portability and ease of use, since the array had to be worn next to the user's skin. The new design had to provide a solution to this problem by appreciably reducing the number of connections between the vibratory array and the electronics of the system.

M-III Audible Noise. Audible noise generated by the transducer while being excited with rectangular pulses was a disturbing factor for the user in the previous system. It was proposed to use a shaped-pulse synthesized from the first 22 components of a rectangular pulse, with the amplitude of each component below a predetermined threshold for noise [15]. This requires a linear channel of amplification so that pulses other than rectangular could be used to excite the transducer. This capability allows investigating the relative trades-off between sensitivity, power consumption and noise when replacing the rectangular pulses with shaped pulses.

M-IV Duty Cycle. In the area of parameter optimization, Taige [14] studied the influence of the duty cycle on first sensation and discrete touch sensation over only a limited range of pulse width (from 0.07 to 0.25 ms) and for a single frequency of 250 Hz. Since it was found that short duty cycle

pulses produced similar sensation thresholds to longer ones³, large power reductions were possible. Therefore, the relationships between duty cycle, frequency, sensitivity and power consumption are key to the design of a portable system. It is the purpose of the present research to investigate the relationships among these parameters to allow optimizing their relationship relative to sensitivity and power consumption.

M-V Frequency. Extensive research has been done in determining the individual response of the mechanoreceptors to various combinations of frequencies and waveforms of stimulation [18, 19, 20, 21]. In these works it was found that for sinusoidal tactile stimulation the most sensitive frequency was around 250 Hz. It appears that there has been no study on optimizing frequency of stimulation for variable frequency and width of rectangular pulses even though rectangular waveforms have extensively been used in tactile information transferring systems. Rectangular pulses require little hardware for generation compared to other more complex waveforms, and, therefore, this investigation is important.

³For duty cycles larger than 1/25.

CHAPTER III

MICROELECTRONIC SYSTEM

3.1 Introduction

The purpose of this chapter is to present the miniaturization, design and implementation of an improved, low-cost, potentially-portable, experimental system, capable of transferring visual images into tactile pictures to aid the visually handicapped, and to compare this design with the previous one. This system is a critical step forward from previous attempts to reduce the size of the hardware and improve the versatility of the system so that the final system can be a practical portable unit. This is a first prototype design from which miniaturization for portability is possible. The new hardware design reduces by a factor of nearly 16 the number of electronic components of the system compared to previous versions. It also reduces the number of connections between the electronics and the vibratory array ¹ to less than 1/10th of previous versions and reduces the power consumption to 1/60th of the previous versions which used continuous stimulation.

In this research, the hardware control part of the system, based on microcomputer systems, was designed to be flexible to permit exploration of the critical parameters of the driving waveform involved in the tactile information transfer. Most of the parameters have been identified in the past and the ranges over which they were tested were specified in [5, 15, 14]. In the present research it is necessary to inves-

¹The vibratory array is a matrix of transducers providing the man-machine interface for tactile information transfer.

tigate the relationships between the parameters, pulse frequency and pulse width of the stimulatory waveform, in order to maximize sensitivity and minimize power consumption (see justification in section 2.9). In the future, once the best combination of parameters is determined, the control part of the hardware can be replaced by dedicated hardware that can be optimized for fewer components.

This chapter discusses the design and development of the hardware and software of the prototype system. The description of the system will be kept to the detail block diagram level because the main contribution of this design is the reduction of the number of components used in the non-controlling part of the hardware by employment of multiplexing techniques. The detailed electronic implementation of the system is based on standard devices of no special interest.

3.2 Main Block Diagram of the System

The system to convert visual images into tactile information must address the three basic problems detailed in section 2.1; image acquisition/processing, hardware control and man-machine interface. The system does this with three main subsystems; the image acquisition/processing subsystem, the hardware control/driving subsystem and the man-machine interface subsystem, Figure 5. Each of these subsystems must address particular problems to achieve the overall objective of converting visual into tactile information. The image acquisition/processing subsystem must acquire and process an image of the environment so that its final resolution matches the resolution of the man-machine interface subsystem. The hardware control/driving subsystem will translate the information coded by the image acquisition/processing subsystem into the signals that will excite the transducers in the man-machine interface subsystem. The man-machine interface subsystem will transfer the information

Figure 5: General block diagram of a system to transfer images through the tactile sense.

coming from the signals generated by the control/driving subsystem into a tactile pattern that the user of the system could interpret.

3.3 System Specifications

In this section a brief description of the parameters that constrained the design of the system will be presented, as well as the assumptions and constraints required for improvements toward portability and for research on waveform parameters. At the end of this section a table summarizing the system specifications is provided. The choices of technology and specific hardware for each of the three subsystems will be discussed in the following sections.

3.3.1 System Resolution

The man-machine interface subsystem is important because it determines the overall resolution of the system. The man-machine interface selected for this research was discussed in detail in Kovach [12]. This man-machine interface [12, 5] represented the best compromise possible, with current transducer technology, between resolution of the tactile picture (16x16 pixels), size of the array of transducers (20 cm x 20 cm), weight of each transducer (2 g), and cost of each transducer (\$0.50). See section 2.4 for a discussion of transducer selection.

3.3.2 Requirements and Assumptions to Improve the System

In section 2.9 was stated the need to redesign a previous version of the system to provide greater capability and size reduction. The revisions included increasing the maximum peak output current to each vibrator, reduction in size, increased versatility of the system, and provision for a shaped pulse for the stimulatory waveform. These requirements are discussed in the following paragraphs.

S-I Maximum Peak Current: It was necessary to increase the maximum peak current per vibrator above the 25 mA used in [5] to provide acceptable levels of stimulation. As shown in section 2.3.4, the mechanoreceptors will respond to sinusoidal stimulation frequencies within a frequency window around 25-800 Hz, having its maximum sensitivity region near 250 Hz. In preliminary experiments with the transducer QMB-105², it was found that sensation thresholds on the forearm could be reached, over the 25-800 Hz frequency region, with peak sinusoidal amplitudes between 40 mA and 120 mA. Nunziata [15] showed that similar peak amplitudes were required to excite sensation threshold while using sinusoidal or rectangular pulses. Thus, these peak values determined for sinusoidal excitation can also be used for rectangular peak currents. Therefore, for research purposes, the system should be able to provide peak currents of at least 120 mA in order to allow determining the sensitivity to various combinations of values of the parameters, such as pulse frequency and pulse width, in regions other than that for maximum sensitivity. According to Craig [22], the ability of subjects to discriminate pairs of patterns

²From Star Micronics Inc.

did not change when the amplitude of vibration was varied from 3 to 28 dB above threshold. It was also found when using the Optacon³ [22], that there seemed to be little correlation between the reading performance and the amplitude of vibration that generated the letters. From this perspective and considering that it is desirable to employ as little power as possible, only 3 dB above threshold for the amplitude of stimulation was specified as being required. The 3 dB condition for the combination of parameters in the most sensitive region, when the threshold is 40 mA, results in a maximum peak current of 57 mA. Therefore, if the system is operated in the region of maximum sensitivity, approximately a 57 mA peak current is required. The vibrator, QMB-105 was rated at 10 mA for rectangular waveform of 50% duty cycle. It was determined experimentally that the QMB-105 can stand rectangular pulses of 50% duty cycle with 120mA peak current during continuous excitation for 2 hours without any significant temperature increase that could be detected by touch. Therefore, the maximum peak current per vibrator was set at 120 mA.

S-II Size reduction and versatility improvement: A preceding prototype [5] connected the array of vibrators to the drivers through 257 lines, which made the array difficult to move around. That prototype was composed of 17 printed circuit boards excluding the microcomputer controlling the hardware, making the system not an acceptable design from

³The word stands for optical-to-tactile conversion. It is a commercially available reading aid for the blind consisting of a small hand-held camera that is scanned across the material to be read. Its output is via a matrix of bimorphs of 6x24 units.

the portability point of view. Thus, it was necessary to reduce the bulk of connections between the vibratory array and the driver subsystem and reduce the number of drivers in the electronic system in order to improve the feasibility of portability and versatility of the system. It was estimated that a good accomplishment would be to reduce the number of connections sufficiently to make possible the use of commercially available flexible cable. As the number of wires in the cable increases, the flexibility decreases. It was found that a 25 wire computer cable was flexible enough for portability purposes. The choice of a 25 wire cable reduces to less than 10% the number of lines when compared with the previous prototype. The driver electronics should not exceed 3 to 4 boards that could be installed in a single box that could be carried with a shoulder strap.

S-III Shaped-pulse driving waveform capacity: In Nunziata [15], it was proposed to use a shaped-pulse instead of a rectangular one to reduce the audible noise produced by the latter in the previous system. This requires a linear channel of amplification so that pulses other than simple rectangular ones can be used to excite the transducers. A control signal to start/stop a waveform generator for this shaped-pulse should also be supplied.

3.3.3 Requirements to Meet Research Needs on the Waveform Parameter Investigation

The system should provide flexibility to test the parameters of the stimulatory waveform presented in section 2.7. The justification for this study was given in

section 2.9. The system should be able to generate the pattern of stimulation shown in Figure 4. This waveform consists of a stimulatory period followed by a recovery time. The stimulatory period is composed of a burst of pulses defined by a pulse frequency and pulse width. It is required to generate a stimulatory waveform with pulse frequency, pulse width, recovery time, number of pulses per burst, and pulse shape all being separately variable.

The required ranges for the parameters of the stimulatory period for a single vibrator are:

P-I Number of pulses per burst (NPB). In [10] it was reported that the shortest excitation is composed of at least 1 pulse, and that for a stimulation burst longer than 20 pulses adaptation starts to become unacceptable. Experiments in [10] showed that for NPB greater than 10, the sensitivity did not increase. Thus, the system should be able to generate a NPB between 1-20.

P-II Pulse width (W) and pulse frequency (F). A previous attempt to study the influence of duty cycle on first sensation threshold [14] was limited only to very short pulse widths between 0.07 and 0.25 ms and to a single frequency of 250 Hz. It is desirable to study the influence of pulse width on sensitivity and power consumption. The range for the pulse width should allow for testing the optimum pulse width for all possible usable frequencies, i.e., from very short pulse width, 0.1 ms, up to $1/F$. In section 2.3.4, it was shown that the three different types of mechanoreceptors are frequency tuned in the range 20–1000 Hz with almost no response toward the lower and higher frequency ends. Thus, the

selected range of frequencies for this study was 25–800 Hz. Experiments performed in [23] and in preliminary testing using the QMB-105 vibrator determined that the minimum pulse width that was perceptible for all frequencies in the range 25-800 Hz, was 0.2 ms. Thus the selected range of pulse widths for this study was between 0.2 and $1/F$ ms ⁴.

P-III Recovery time: In [10] it was hypothesized that the longer the duration of the recovery time, the greater should be the recovery of the sensitivity of the tactile receptors and the lower the average power delivered by the system. The recovery time plus the stimulatory period set the sampling rate for the images being presented to the subject. A fast rate of information transfer is required when moving objects are considered. Nunziata [10] tested recovery times in the range between 0.1 and 10 s. In that study it was reported [10] that for recovery times longer than 2 s, the subjects experienced difficulty remembering the previous stimulation. For recovery times shorter than 1 s adaptation begins to increase the sensation thresholds. The optimum recovery time was selected to be around 1 s. Since there might be situations in which a faster frame rate is required at the expense of more power consumption, the system should provide a range of recovery times that allow selection of optimum configuration for motion and static recognition. Craig [24] found that masking caused by presentation of two consecutive letter patterns to the finger could be avoided if the interstimulus interval was kept longer than 200 ms. Therefore, the recovery time should be larger than 200 ms. To avoid

⁴The largest pulse width is $W=1/F=40$ ms for a frequency of 25 Hz.

large power consumption because of adaptation, a range for the recovery times around the optimum for sensitivity, i.e., 1 s, was chosen. The minimum recovery time should be greater than 200 *ms*. Therefore, for research purposes, the range for the recovery time was selected between 500 *ms* and 1.5 s.

P-IV Gray levels: Most of previous systems have provided simple binary or three levels of gray. No testing has been done to determine an appropriate number of gray levels. In this system, 4 levels of gray will be provided to be able to determine in the future if recognition is enhanced by adding more levels of gray to the basic binary coding.

3.3.4 Requirements to Meet Research Needs in Image Processing Enhancements for Tactile Information Transfer

It is also desirable to study the effects of image processing techniques such as, edge enhancement, normal/reverse video, median filtering/averaging, on the sensation and recognition thresholds. Therefore, the system must be able to provide for capabilities for these types of processing.

3.3.5 General Considerations

The total cost should be kept to a minimum, not to exceed the cost of commercially available audio/video systems because the system is intended to be accessible to a large part of the blind community. If possible, the system should be built with hardware available off-the-shelf. This will keep the cost down and provide ease of repair. The system should be designed to be as close as possible to a usable prototype while still providing the required flexibility for the research. It is desirable that the

system provides the capability of adjusting the different parameters of the waveform by software programming rather than by hardware modification.

3.3.6 Portability versus Flexibility

There are two apparent conflicting goals in this design. One is the move toward portability of the system and the other is the requirement that the system should be flexible enough to conduct multiple tests. Even though there is some compromise between size and flexibility, the electronic system can be considered to be composed of two parts; one is the control unit of the circuitry and the other part is composed of the drivers and amplifiers for transferring the information. This second part will be reduced in size by reducing the number of amplifiers required per transducer and by reducing the number of connections between the driver in the electronic subsystem and the transducer array. The control part of the electronics is not being reduced in size since it requires flexibility and, ideally, programmability to perform the testing. Once the research on parameter testing has concluded, the control modules can be redesigned to be simpler and smaller.

3.3.7 Summary of Specifications

Table 1 shows a summary of the specifications discussed in section 3.3.

3.4 Circuit Size Reduction Strategy

3.4.1 Statement of the Problem

As explained in section 3.3.1, the system is composed of three subsystems; image acquisition/processing subsystem, hardware control/driving subsystem and man-machine interface subsystem. The previous specifications of the man-machine

Table 1: Specifications and Requirements for the System

Man-Machine Interface	
Resolution	16x16 (12 mm separation)
Transducers	QMB-105
System Improvements	
Maximum peak current	120 mA
Size Reduction	3-4 boards
Versatility	≤ 25 lines connection
Amplification channel	linear for shaped pulse
Research Parameters	
Number of pulses per burst (NPB)	1-20
Pulse width, W	0.1-40 ms
Frequency, F	25-800 Hz
Recovery Time, RT	0.5-1.5 s
Number of gray levels	4
Image Processing	
High to low resolution conversion	Averaging
Outlining	Edge enhancement
General Considerations	
Cost	Low cost (Audio/video appliance)
Control over parameters	software control
Availability	off the shelf where possible

interface subsystem required the resolution of the system to be 16×16 . This implies that a maximum of 256 transducers will be excited with stimulatory waveforms.

In previous research [5] the problem of transferring the information from the low resolution image to the 256 transducers was solved by devising a separate driver for each transducer. Each driver transformed the information coded in the 16×16 low resolution image into an electrical waveform that excited its transducer.

The problem to be solved by the hardware control/driver subsystem is to transfer/convert the information stored in a 16×16 low resolution image to the man-machine interface subsystem consisting of 256 transducers. The problem must be solved using a minimum of hardwire connections between the two subsystems.

3.4.2 Time Division Multiplexing

It was shown [14, 10] that short duty cycle stimulation, as short as $1/25$, using rectangular waveforms produces similar sensitivity to longer duty cycle waveforms. For a 250 Hz rectangular waveform, it was found [10] that pulses as short as $1/25$ duty cycle, i.e., pulse width of 0.16 ms, could be used without significant loss in sensitivity. Therefore, the stimulatory signal described in section 2.7 becomes a burst of very short pulses followed by the recovery time.

Signals can be separated from each other if they do not overlap either in the time or frequency domain. A pulse modulated waveform, such as the stimulatory waveform, has moments at which its amplitude is zero. When two or more waveforms are added together in such a way that they do not overlap in time, they are said to be time division multiplexed [25]. Multiplexing is commonly used in communication systems when a group of data lines in one location and another group of lines in a remote location require connection via a single link between the two locations [26].

The time division multiplexing technique can be employed to transfer the information from the low resolution image to the man-machine interface with few wired lines.

3.4.3 Multiplexing Stimulatory Waveforms

The number of data lines that can be multiplexed in a single line is limited by the pulse width needed to be transmitted through the single line. Previous research indicated that the duty cycle in the stimulatory waveform could be reduced to a minimum of $1/25$. This means that the theoretical maximum number of lines that could be multiplexed into one would be 25. Since there is time involved in switching and latching the data from each line, it is expected to have fewer than 25 lines multiplexed into one. The condition is: $(W + SL) * n = 1/F$, where W is the pulse width, SL is the time required for switching and latching the data, n is the number of lines to be multiplexed and F is the frequency of the pulse modulated signal. For example, for 250 Hz and a pulse width of 0.2 ms, and for the ideal case of $SL = 0$, the maximum number of lines that could be multiplexed would be $n = 20$. Therefore, any number of lines lower than 20 could be multiplexed together to reduce the number of drivers and links to the man machine interface.

For the research on waveform parameters that require longer duty cycles, the investigation can be limited to smaller regions of the vibratory array, i.e., fewer lines can be multiplexed to obtain longer duty cycles. This is at the expense of number of vibrators being stimulated each time the array is scanned. Nevertheless, for experiments requiring optimization of sensitivity and power this is sufficient.

3.5 Rationale for the Selected Design

In this section, options available for the design of the system will be presented. Certain parts of the hardware were already specified by previous research at the time of the design. Therefore, selection of this hardware was straightforward. The design choices and trade-offs are related to the system specifications and system requirements presented in section 3.3.

The three main problems detailed in section 2.1, image acquisition/processing, hardware control/driver and man-machine interface, were addressed with different subsystems of the hardware. The choices of technology and devices for the system, have been extensively covered by Kovach in [12] for the man-machine interface transducers and by Kirschner in [5] for the image acquisition/processing subsystem.

3.5.1 Image Acquisition/Processing Subsystem

The image acquisition/processing subsystem must provide at least two modules; an input sensor module to acquire information about the environment and an information processing module to manipulate the input data from the input sensor and provide an appropriate output, in resolution and information coding format, to interface the hardware control/driver subsystem.

I-I Input sensor: As explained in section 2.1, several physical means are available to acquire information about the environment. An optical sensor was chosen for this research because its output closely resembles the information gathered by the eye and because it does not require the emission of energy into the environment. Given the limited resolution of the man machine interface, 16x16, the optic sensor does not require

very high resolution. Other factors such as size, weight and cost were considered in [5] to select a camera. The choice of an input sensor was a camera based on an optic RAM IS-32 which was low cost, small and provided adequate resolution, 128x128, for the input picture. The system was implemented using this optic RAM IS-32 camera. However, while performing tests with blind subjects on camera handling, it became apparent that the lack of automatic focusing and aperture control, made the camera difficult to control. In the meantime, prices on CCD auto-focus, auto-aperture control cameras became reasonable, and therefore a new implementation using a Sony CCD-TR5 was made [27]. Both implementations of the image acquisition subsystem are similar. In this document, details of mainly the first implementation will be given. More details on the upgraded version of the camera can be found in [27].

The camera can be connected to a computer through an interface board that comes with the camera. The output of the camera is serial data at software selectable baud rates of up to 153,600 baud. The camera provides only two gray levels, making the threshold for black/white decision a major factor in the image acquisition. The exposure time can be specified by sending commands through a data port in the interface board. This data port also allows for checking camera interface status, for the selection of data rates and format of the data. All these parameters are controlled by software that controls the camera and directs the acquired images to be stored in the memory of the computer.

I-II Information processing module: The information processing module is required to convert the output from the camera or camera interface into a form that will be usable by the driving circuitry of the vibrotactile array. The primary task of this module is to convert a relatively high resolution image of 128x128 to a 16x16 low resolution one which can be presented to the user by the transducers of the man-machine interface. The information processing module should be capable of manipulating the data to reduce the resolution of the image. The information processing could be hardwired with all processing algorithms predetermined and fixed, or could be programmable, allowing flexibility for changes by software. Given the flexibility required for the testing purposes, which include the generation of artificial patterns, a programmable information processing module was chosen. In the present design an IBM-XT-286 6 MHz was preferred over the original Apple IIe selected by Kirschner [5]. This selection, besides providing an upgrade in the speed of the processing, made available at relatively low cost extensive scientific software and hardware developed for IBM compatible microcomputers.

It was determined that in order to perform tests involving controlled movement of the camera by the subject, more than one processed image per second was required. The IBM-XT-286 6 MHz was able to provide a maximum of 1.3 images per second. In order to increase the frame rate to 2 or 3 per second it was necessary to upgrade the information processing module to a 386/SX-20 MHz microcomputer. The maximum frame rate with this microcomputer is 2.8 frames per second.

3.5.2 Hardware Control/Driver Subsystem

The hardware control/driving subsystem translates the information coded in the low resolution image into the signals that will excite the transducers in the man-machine interface subsystem. The hardware control/driver subsystem is composed of two modules; a hardware control module and a hardware driver module.

H-I Hardware control module: The hardware control module directs the data manipulation and hardware to generate the specified stimulatory waveform. It should provide enough flexibility to vary all the parameters of the stimulatory waveform as specified in section 3.3 for research purposes. Since the research on the parameters requires modification of pulse width, frequency, recovery time, pulse shape, number of pulses per burst, mode of presentation, etc., a flexible programmable controller was necessary. A controller board should control all these operations. This board should be compatible with the image acquisition/processing subsystem and offer additional developmental tools to ease the development of the software modules at a relatively low cost. A microcontroller was chosen for this application because it offers the same flexibility as the microprocessor but it contains RAM, ROM and input/output capabilities within a single chip. The main objective of the microcontroller is to provide an integrated facility to support real-time control on a single chip. The FX-97 board based on the Intel 8097 microcontroller operating at an effective clock cycle of 4 MHz was chosen as the hardware control module because it has the development tools required, it is compatible with the IBM microcomputer chosen for the image acquisition/processing

subsystem and because of its relatively low cost of \$500.

H-II Hardware driver module: The hardware driver module should provide the hardware to transfer the signals and provide adequate amplification levels to excite the array of transducers in the man-machine interface subsystem. The stimulatory waveform is composed of a stimulatory period followed by a recovery time. The stimulatory period is composed of a burst of short pulses that according to the discussion of section 3.4.3 allows the multiplexing of several lines into one between the hardware control/driver subsystem and the transducers in the man-machine interface subsystem. According to the sensitivity tests for a rectangular 250 Hz waveform [14], 0.2 ms was the minimum pulse width required so that no significant loss of sensitivity resulted. This result limited the maximum number of lines to be multiplexed to a number of 20. If longer pulse widths are to be used, the maximum number of lines will decrease. In addition, considering that the low resolution image is composed of 16 columns and 16 rows and that in many hardware devices such as multiplexers, demultiplexers, counters, etc., the number of channels and input/outputs are multiple of 2, a natural choice for the multiplexing process was 16 lines. In this way a complete column or row could be transferred in parallel, simplifying the addressing operations to 16. Therefore, the system could be ideally operated at a maximum duty cycle of $1/(\text{number of columns})$, in this case this is $1/16$. This requires providing a total of 16 drivers to transfer the excitatory waveforms to the transducers. The drivers chosen to transform the coded low resolution image into rectan-

gular pulses of 4 different amplitudes were programmable amplifiers. The rest of the hardware, which consists mainly of power amplifiers, multiplexers, switches and glue logic, are commercially available devices.

3.5.3 Man-machine Interface Subsystem

The main components of the man-machine interface subsystem are the transducers. The transducer QMB-105 from Star Micronics Inc. was selected by Kovach [12] as the most suitable transducer for the application of transferring information through the skin. This transducer, as explained in section 2.4, is low cost, small relative to other transducers and requires low power to produce excitation of the mechanoreceptors of the skin. The same transducer was used in this development.

Since the number of connections between the transducers and the hardware control/drivers electronics was reduced by multiplexing 16 stimulatory waveforms into one line ⁵, at the man-machine interface end the demultiplexing process must separate each waveform and assign it to the corresponding transducer. A board based on a 16 channel multiplexer and transistors was devised to accomplish this objective. The detailed implementation is shown in Figure 8.

3.6 General Configuration of the System

In section 3.5 the rationale for the selection of the main components of the system was given. Based on that selection, the general configuration of the system is as follows:

⁵See section 3.4.3.

The image acquisition/processing subsystem is composed of a Sony CCD-TR5 8 mm video camera ⁶ and the IBM 386SX-20 which controls the image acquisition and the image processing. The hardware control/driver subsystem is composed by the FX-97 board ⁷ and a set of 16 programmable amplifiers, 16 power amplifiers, switches, multiplexers and glue logic. The generation of the stimulatory waveform and the final information transfer to the vibratory array is controlled by the Intel 8097 microcontroller. The man-machine interface subsystem is composed of a demultiplexing board and 256 miniature audio transducers, QMB-105 from Star Micronics Inc., which translate the electrical driving waveform into skin displacement to excite the tactile receptors.

A block diagram of the system is shown in Figure 6. The block shows the camera (a SONY CCD-TR5 8mm video camera), an image acquisition/processing microprocessor (the microcomputer 386/SX-20 MHz), a microcontroller board (FX-97 based on the Intel 8097 chip), a wavegenerator circuit that generates shaped-pulses ⁸ a programmable amplifier board with power amplification stage, an analog demultiplexers board and an array of 256 vibrators.

⁶This camera replaced the optic RAM IS-32 camera of the initial implementation.

⁷This board is based on the Intel 8097 microcontroller and provides additional RAM, EPROM and input/output capability.

⁸The operation of this wavegenerator will not be discussed in this document, but any wavegenerator circuit with an input line to start/stop the generated pulse will qualify for this system.

Figure 6: System Block Diagram

3.7 System Operation

3.7.1 Image Acquisition/Processing Subsystem

The prototype system operates with the microcomputer and the microcontroller working in parallel. The image acquisition processor acquires a 256x256x8 pixel⁹ image through the video camera. According to the specifications of the man-machine interface the image must be reduced to a 16x16 pixel resolution. Several algorithms can be used to reduce the image resolution; averaging, median filtering and other filtering techniques. Averaging was selected because it is faster than any of the filtering techniques and gives good practical results. Therefore, the image is processed by averaging 16x16 pixel blocks of the high resolution image to produce 1 pixel of the low resolution image. Since the number of gray levels determined in the specification of the system is 4, the results are coded into 4 possible levels of gray using two bits. At this stage further processing of the image, such as edge enhancement or normal/reverse video are possible. It is not possible to perform any further image processing in the high resolution image because of the long processing time involved. After the image processing is over, the coded low resolution image needs to be transferred to the hardware control/driver subsystem. A serial communication was chosen since the FX-97 board had a serial port built in and the 386SX-20 MHz microcomputer, also, had available a serial port. In order to send the data serially two pixels were combined into 1 byte, compressing the data into 128 bytes and shortening the transmission time to 1/2. In case a faster transmission rate is required, a maximum of 4 pixels per byte could be combined, compressing the data to 64 bytes. Once the low resolution image has been transferred to the FX-97 board, the image acquisition

⁹In the Sony CCD camera implementation.

processor starts immediately acquiring a new image while the microcontroller starts to transfer the low resolution image to the vibrotactile array.

3.7.2 Hardware Control/Driver Subsystem

The microcontroller must receive the data coming serially from the image acquisition/processing subsystem. The communication could be implemented either using interrupts or polling operation. The task the microcontroller is executing, which is control of the hardware to generate the stimulatory waveform, is much shorter than the task the image acquisition/processing processor is performing. The microcontroller needs to wait for the new image coming from the serial port after it has finished generating the burst of pulses for the stimulatory waveform. Therefore, since the controller is not performing any other task after the waveform is generated, it can be set in polling mode, waiting for the image acquisition/processing subsystem to send the coded image. In addition, polling is simpler to implement and does not provide any disadvantage with respect to the interrupt mode in this situation. For example, after the microcontroller receives the coded image, it would take only around 40 ms to generate a stimulatory waveform at 250 Hz, 10 pulses per burst and pulse width of 0.16 ms. This time is small compared to the 250 ms that it takes to reduce the high resolution image to a low resolution one or to the recovery time (500 or $1000 \leq ms$).

The microcontroller decompresses the data, stores the image in memory and implements the multiplexing of the 16 rows for each column as explained in section 3.4.3. For this purpose the microcontroller transfers the image to the programmable amplifier board one column at a time in a sequential manner. The gain of a group of 16 programmable amplifiers is step controlled to provide 4 possible gray levels

according to the column being transferred. Then the controller board activates the wave generator, causing the shaped pulse to be amplified in each of the 16 programmable amplifiers according to the gain just previously set. The pulse output from each programmable amplifier goes to a power amplification stage consisting of a set of 16 power amplifiers driving the 16 transducers in a column. The process then repeats for the rest of the columns. When the microcontroller finishes with the 16th column, it enters the polling mode waiting for the next image to come.

The process for the whole array (16 columns) is repeated NPB times to produce the required number of pulses per burst. The total time required to generate two adjacent pulses for the same vibrator has to comply with $1/F$, where F is the desired frequency of the stimulatory part of the waveform.

3.8 Multiplexing Scheme

As a result of the pattern of stimulation, each image is sent NPB times to the vibratory array in the period $NPB \cdot (1/F)$. The multiplexing scheme resulting from the column scanning mode is shown in Figure 7. During the stimulatory period of the waveform, the pulses are $1/F$ s apart. The rest of the columns are scanned in the period of no stimulation between pulses.

3.9 Detailed Block Diagram

Figure 8 shows a detailed block diagram of the system without the image acquisition subsystem. The microcontroller governs the operation of the remaining hardware through 12 lines. Four lines are used to encode amplitude values from two adjacent pixels (one pair for each pixel) and set the amplification level of two programmable amplifiers simultaneously. Three lines are used to select the pair of

Figure 7: Multiplexing Scheme for the 16 columns

programmable amplifiers being accessed at each amplitude loading operation. One line is used to start/stop the shaped-pulse wavegenerator. The last four lines are used to select the column in the vibratory array where the signals coming from the programmable amplifiers are targeted.

On the vibratory array, the column to be excited is selected using transistors as switches. A 16 channel multiplexer supplies a logic high to the base of the 16 transistors in that column, closing the switch and providing a ground return to all vibrators in that selected column.

3.10 Timing Considerations

There are some relevant timing considerations and several speed limits in the system that will be discussed in this section.

3.10.1 Microcontroller Timing of Operations

The microcontroller operates at an effective clock cycle of 250 ns ($12 \text{ MHz} / 3 = 4 \text{ MHz}$). All operations of the rest of the hardware are sequentially governed by the microcontroller. Any operation controlled by the Intel 8097 requires a LOAD operation in order to output a signal on the lines that control the hardware. A LOAD operation requires a minimum of 4 clock cycles to execute and therefore they do not occur faster than $1 \mu\text{s}$ apart. The maximum propagation delay time on the multiplexers, programmable amplifiers, switches and glue logic being used is less than 450 ns. This delay time is smaller than the $1 \mu\text{s}$ required by the microcontroller between operations and therefore satisfies all critical timing requirements for the components used in this design.

Figure 8: Detailed Block Diagram of the System

The total number of operations the Intel-8097 must control are shown in Figure 9. In order to transfer one column to the vibratory array, the microcontroller must perform 8 amplitude loading operations (load 16 programmable amplifiers in pairs), start the pulse, wait for the length of the pulse and stop the pulse, and finally wait to meet the required $1/F$ period.

Figure 9 (a) shows the pattern of stimulation that should be provided to any vibrator that is "on". Figure 9 (b) shows the expansion of the time between any two pulses for a particular vibrator. During this time between pulses, the microcontroller has to reload and start/stop the pulse generator 16 times in order to scan the whole array. Figure 9 (c) shows the operations required to load one column: 8 loading operations of the programmable amplifiers, the pulse generation, and the Wait period to meet the $1/F$ requirement.

The total loading time (8 pairs of programmable amplifiers) was measured to be $70 \mu s$. The speed limitation of the hardware control/driver subsystem can be specified by the following equation:

$$16(8Load + W + Wait) = 1/F \quad (3.1)$$

where Load is the time in ms needed to load one pair of programmable amplifiers, W is the width in ms of the pulse, Wait is the waiting time to reach the desired frequency F in Hz. F is the frequency of stimulation during the stimulatory part of the waveform. If this route becomes critical, the number of programmable amplifiers loaded in parallel could be increased and thereby the speed of the subsystem will be incremented. Another means of increasing the speed of this path is to upgrade the microcontroller to another with an effective clock cycle shorter than 250 ns.

Figure 9: Timing scheme. (a) Pattern of stimulation. (b) Expansion of one period between two consecutive pulses. (c) Expansion of the period of loading for one column.

3.10.2 Serial Transmission: Image Acquisition/Processing - Hardware Control/Driver Subsystems Speed Limit

The information corresponding to the 256 pixels of the low resolution image was coded in 128 bytes because only 4 gray levels are being used. The serial communication is operated at 9600 baud and therefore to transfer 128 bytes takes approximately 106 ms. This limits the maximum number of images that could be transferred per unit time assuming that the recovery time could be shortened as desired. This speed limit could be extended by coding 4 pixels per byte and transferring only 64 total. In this case at 9600 baud the total time required would be around 53 ms. Another alternative is to use a parallel link between the image acquisition/processing subsystem and the hardware control/driver subsystem.

3.10.3 Image Acquisition/Processing Subsystem Speed Limit

The third speed limit in the system is in the image acquisition/processing subsystem. The image acquisition and processing required to acquire the 256x256 image and reduce it to the low resolution one (16x16) takes about 0.25 s. The data coding and transfer at 9600 baud takes about 0.1067 s. The maximum number of frames per second that the system is able to transfer from the image acquisition/processing subsystem to the hardware control/driver subsystem is 2.8. An alternative to increase the speed of this subsystem is to write some of the software which currently is in Turbo C in assembly language, optimizing it for speed. By reducing the time spent in the serial transfer between the image acquisition/processing subsystem and the hardware control/driver subsystem, the number of frames per second could be increased up to a maximum of less than 4 frames per second. More complex modifications could consider the use of dedicated hardware for some of the image processing.

Nevertheless, before any further speed upgrade, it should be determined if the tactile sense will reach a "fusion" point beyond which the frame rate does not affect the tactile sensation.

3.11 Software Modules

In this section a brief description of the various software modules that control the operation of the system are described. There are two main software modules in the system. One that handles the image acquisition/processing task and a second for the control of the hardware for generating the stimulatory waveform that goes to the transducers. The first software module runs in the 386/SX-20 microcomputer and the second one in the FX-97 microcontroller board.

3.11.1 Image Acquisition/Processing Software Modules

This software is written in Turbo C (Borland 1.5) and consists of a main program with several modules. As explained before, two camera implementations were made. The software modules are very similar in both implementations. The first implementation will be discussed here since it is the one implemented by the author of this document. The second implementation, which is an upgrade of the first one, is discussed in detail in [27].

IS-I Initialization and control: This module initializes the frame grabber and defines pointers to be used in the pixel handling. In the first ¹⁰ implementation of the camera, the image acquisition was done in a serial manner at 153,600 baud from the optic RAM of the camera to the IBM.

¹⁰The detailed description of the implementation of the Sonny CCD-TR5 camera is discussed in Spisz [27]

This module controls the acquisition of the data from the camera and its storage in the video-memory of the microcomputer for display and later processing.

IS-II High to low resolution image conversion A 256x128x1 image is received and stored in the video RAM memory of the microcomputer to visualize the acquired image. Only the first 128x128 pixels of the image are selected for further processing. This software module uses pointers to average the relatively high resolution image in blocks of 8x8, reducing the resolution to 16x16x2 (with 4 gray levels). The averaged image is also displayed by storing it in the video memory of the microcomputer.

IS-III Optional outlining: An optional module extracts edges from the averaged image using a 3x3 Laplacian operator. The results are displayed on the monitor as well as by storing the results in video-memory. Outlining of the high resolution image is not possible at this point because the processing time is too long for real time information transfer.

IS-IV Coding for serial transfer: The last module of the first implementation combined two pixels in one byte to transfer serially a total of 128 bytes to the controller board. The new implementation of the camera offers, in addition, menu selection of alternatives and normal/inverted modes.

3.11.2 Hardware and Scanning Control Modules

This software is composed of a main program written in C (Archimedes cross compiler) and a subroutine written in assembler 8096. This software runs on the 8097 microcontroller board.

HC- Main program (FX-97 board): The main program initializes the pointers and a serial port (8256) to receive the serial communication from the image acquisition microcomputer and calls the assembly language subroutine.

HC- Subroutine (FX-97): This subroutine, written in 8096 assembly language controls all the necessary operations to: 1) store the 16x16 image coming via the serial communication from the image acquisition/processing subsystem, 2) transfer this image data, column by column, to an array of 16 programmable amplifiers, 3) generate the appropriate signals to: 2 lines containing the amplitude information, 3 lines containing the row selection of the pair of programmable amplifiers, 4 lines controlling the column selection in the vibratory array and 1 line to control the start/stop of the wavegenerator.

This routine has as inputs the number of pulses per burst, pulse width, Wait period and recovery time. The program first selects the pairs of programmable amplifiers using the 3 control lines, loads the required amplification level in each one, repeating the process 8 times until the 16 are loaded. Then, the line that controls the wavegenerator pulse is activated and a loop is set to wait for the duration of the pulse. When the loop finishes, the line is deactivated and the pulse is stopped. Next, a loop is set to wait to complete the required time to meet the period of the waveform as shown in Figure 9 (c). Once this loop is over the controller starts with the next column, repeating the above described process. After the whole array has been scanned once, the program repeats itself a

number of times equal to the NPB.

At the end the routine enters in polling mode waiting for a new image coming from the image acquisition subsystem. The routine was optimized for speed rather than for size. The blocks controlling amplitude loading operations were written explicitly instead of using a loop implementation.

3.12 Operation of the System with Visually Handicapped

The system has been operated for more than a year while running various series of psychophysical tests. Some of the results have been presented in the 1990 North East Bioengineering Conference [23]. Details of specific tests carried out to investigate the influence of some parameters of the waveform on sensitivity and power consumption will be described in chapter IV.

The system was demonstrated and used for data gathering from the blind community at the 1990 meeting of the American Council of the Blind, Ohio Chapter, on October 19-20, 1990. The main objectives were to obtain direct input and response of the blind in testing the system. Part of the testing consisted of conducting a shape recognition experiment that will be described in the following sections.

3.12.1 Shape Discrimination Test

In order to verify the response of the blind population to the system, a test was designed to evaluate the ability of blind subjects to discriminate among simple geometric objects. This test focused on the subject's ability to discriminate among objects of different shapes but of equivalent size so that similar numbers of vibrators were excited with each shape. This eliminated the possibility of recognizing objects

just by recognizing size. The subjects had control of the camera to point selectively at different shapes of white paper placed over a black background. The subjects had a 5 minute familiarization period with the system followed by a learning period in which the three objects used in the test were repeatedly identified and presented to them. After the 5 minute learning period the subjects were tested for recognition of the objects.

3.12.2 Methods

The subjects wore the tactile array on the abdomen and hung the CCD-TR5 videocamera from their neck using the shoulder strap. They pointed the camera with their hands toward the objects in front of them. The test consisted of the static presentation of three white paper solid shapes on a black background. The three shapes were a circle, a square, and a triangle, all of comparable areas.

After the learning period, each subject participated in a single test of 10 trials in which the three shapes were presented in random order. During the test positive feedback was given. Because of the similar areas the three shapes covered, the vibrational images differed only in a few vibrators on the edges of the shapes. All results were based on ten trials, except for subjects E.F. and D.P. who were tested only 8 times.

3.12.3 Shape Discrimination Results

Table 2 presents the summary of the results on basic shape discrimination. The correct answers are given as a percentage of the total answers given by the subject during the test.

Table 2: Discrimination between basic shapes

Subject Initials	Sex	Age Range	Correct Answers %
T.T.	M	late 20's	80
J.N.	F	early 30's	80
J.M.	F	early 30's	60
J.P.	M	early 30's	100
M.B.	M	early 30's	90
S.W.	F	mid 30's	90
D.P.	M	mid 30's	63
D.K.	F	early 40's	80
I.H.	M	mid 40's	40
E.F.	M	early 50's	75
R.R.	M	mid 50's	30

Results show that most of the subjects were able to discriminate very well between the three basic shapes. Six of the 11 subjects were able to recognize shapes with a percentage of correct answers of 80 % or above. It was found that subjects who did best were those who had had previous training with other technological devices to aid blind people. It was noted that longer learning periods might be required for some people.

A more informal test was also carried out to see if some of the subjects could recognize faces. In general, the subjects that did best in the shape recognition discrimination test, also did best in the face recognition test. A human face was presented and contrasted with a solid circle of similar size. Some of the subjects were able to determine that the human face had a mustache and one of them was able to recognize glasses on the face, which was remarkable.

3.13 Validation of the System and Discussion

All the specifications of the system were met in the new implemented design.

Val-I Peak current. The system is able to provide 120 mA peak current for pulses of 0.1 ms. For pulses wider than 0.2 ms the maximum is 130 mA. This is due to the inductive component of the vibrator, which was measured to be 3.25 mH. The time constant for the rise time is 0.065 ms. The shortest pulses used in the parameter optimization investigation (see Chapter IV) was 0.2 ms. This means that the peak current would have reached more than 95% of its maximum by the time the pulse began to fall.

Val-II Size and versatility. The number of lines from the system to the vibratory array was reduced from 257 to 22. Only 22 wires are being used in a 25 wire (24 AGW) computer cable, this providing the required flexibility of motion for the array. An additional 30 ft cable was supplied to provide mobility to the user at some distance from the system. The microcontroller, drivers and additional electronics are still on experimental bread boards inside a single box which is not portable. If desired, a portable prototype including the hardware driver/control subsystem, a unit including 3 or 4 boards, could be constructed. The present design is a step forward toward portability of the system. The present hardware can be miniaturized with some loss of flexibility by replacing the flexible modules with dedicated hardware once the experimental investigation of parameters is finished.

Val-III Linear amplification channel. The system is able to generate shaped pulses as required by the specifications. It should be decided in the future whether shaped pulses improve the recognition, sensitivity or noise suppression enough to justify the extra hardware required.

Val-IV Number of pulses per burst. The NPB is controlled by a counter and is an integer number that can go from 0 to 256, the higher limit given by the 8-bit size counter. This range covers more than that required by the system.

Val-V Frequency and pulse width. The frequency together with the pulse width during the stimulatory period is an input to the program. With these two quantities a program calculates the number of loops required for the pulse width and for the Wait period after the pulse. These are two different software loops. Each step is $4.3 \text{ E-}06$ and $4.359 \text{ E-}6$ for the pulse width and Wait period, respectively. Therefore, the finest step in adjusting the pulse width and frequency is around $4 \mu \text{ s}$.

Val-VI Recovery time. This time is controlled by the image acquisition subsystem and can be adjusted much more accurately than is required, because the processor is running at 20 MHz and a very short loop can be set up. Therefore, the 0.5–1.5 s range required in the specifications of the system is easily achieved.

Val-VII Limitations. The main limitations of the present system are: The maximum rate of frames per second that can be transferred is 2.8/s. The maximum pulse width duty cycle that the system is able to generate for any given frequency is smaller than 1/16. The system is able to present

only one column in parallel but all the 16 columns, i.e., the whole image, could be scanned in $(W \text{ ms} + 70 \mu\text{s}) * 16$, where W is the desired pulse width and $70 \mu\text{s}$ is the time required to load the programmable amplifiers. For example, for a pulse width of 0.5 ms , the whole image will be scanned in 9.12 ms . This time seems small when compared to the recognition time required by the subject [5].

Val-VIII Peak power delivered. There is an added advantage to the multiplexing scheme employed in this design. The maximum peak power required by the system is only $1/16$ of the peak power required for a totally parallel implementation. For example, for the case where all pixels in the image are "on" (worst case), and assuming the subject is using a peak current of 80 mA , the total peak current required by the system would be 1.28 A . This represents a total peak power delivered by the system of 5.76 W . In the case of the parallel implementation the total peak current required will be 20.48 A , which represents a total peak power of 92.16 W .

Val-IX Average power delivered. For a 100 Hz rectangular stimulatory waveform with recovery time of 0.5 s , pulse width of 0.5 ms and 10 pulses per burst, the reduction on average power consumption per cycle relative to the same 100 Hz continuous rectangular waveform of 50% duty cycle was by a factor of 60.

CHAPTER IV

OPTIMIZATION OF DRIVING WAVEFORM PARAMETERS FOR VIBROTACTILE INFORMATION TRANSFER

4.1 Introduction

The purpose of this chapter is to present the investigation on the basic parameters of the driving waveform to optimize their relationship relative to skin sensitivity and power delivered to the vibrator.

The usefulness of systems designed to transfer information through the skin depends on their portability and wearability [2]. The bulk, weight and power inefficiency of systems implemented in the past have hindered the realization of such a system [2]. Reducing the power required by the system, by optimizing the excitatory waveform parameters for maximum sensitivity and minimum power, is a necessary component to the solution of the overall problem.

4.2 Research Considerations and Assumptions

Although many efforts have been made in the past to build systems to transfer information through the skin tactile sense, little attention has been given to the properties of the driving waveform for the vibrators. Many investigations have shown that the skin mechanoreceptors are most sensitive to sinusoidal mechanical stimulation around 250 Hz [7, 28, 29]. See the mechanoreceptor frequency response in Figure 2. It appears that there have been no studies relating wave-shape and sensitivity.

Nunziata [15] showed that by employing rectangular pulses of short duty cycle, equivalent sensation could be elicited with less power than that for sinusoidal stimulation. Taige [14] and Nunziata [10] showed that by shortening the duty cycle of rectangular waveforms of 250 Hz, equivalent sensation could be reached with roughly the same amplitude as with longer duty cycle, but with a reduction in the amount of power delivered by the system.

In previous studies it was assumed that the optimum frequency for the excitatory period was 250 Hz regardless of the waveshape. This assumption may not be valid, because changing the waveshape from sinusoidal to rectangular changes the distributions of the resulting frequency components of the spectrum. Therefore, instead of having the energy concentrated in a single frequency of 250 Hz, as in the case of the sinusoidal waveform, the rectangular waveform will distribute the energy among the component frequencies. The resulting sensation will be a result of the excitation of the different mechanoreceptor types targeted by the range of harmonics of the rectangular waveform.

Since changing the pulse width and the base frequency on a rectangular waveform changes the distribution of the resulting frequency components, and because the mechanoreceptor sensitivity varies along the frequency axis, it was the hypothesis of this study that the optimum for sensitivity and power consumption would be a function of the frequency and the pulse width. Therefore, it was proposed to study the extent to which the parameters of the waveform that have an effect on the spectral distribution of the harmonics of the excitatory waveform alter the sensitivity and power consumption.

In a previous study [15], the noise produced by the rectangular pulses while exciting the QMB-105 audio transducer was considered objectionable, and a shaped

pulse was designed to reduce the noise level. For this purpose, the amplitude of the first 22 harmonics of the rectangular waveform were reduced to under a predetermined threshold for noise, synthesizing a shaped pulse by adding these harmonics. The system designed for the research on the parameters of the driving waveform, presented in Chapter III, is capable of generating either such shaped or rectangular pulses. The spectral distributions of the shaped and rectangular pulses are very similar, because the shaped pulse is constructed from the first 22 harmonics of the rectangular waveform with somewhat reduced amplitudes to control noise. Thus, optimization of parameters for the rectangular waveform should yield similar results to those expected for the shaped pulse. With the present hardware implementation of the system, it was found that the audible noise generated by the rectangular pulse is not as disturbing as originally thought. Once the array of vibrators is placed on abdomen of the user, the audible noise is just about perceptible. Thus, the noise problem became a secondary issue in the design of the system. Keeping in mind that the overall objective of this research is to study the parameters of the stimulatory waveform that would allow producing sensation with minimum power, the inclusion of additional hardware to produce the shaped pulses increases the required power consumption and the chip count, i.e., circuit size. Rectangular pulses do not require additional hardware for generation, and from the hardware point of view this is a preferred choice over other waveshapes. Other techniques to reduce the audible noise, that would not require additional hardware, can be investigated, e.g. opening small perforations on the steel plate of the vibrator to reduce the air being pushed by the plate and therefore the noise [30]. Therefore, for this research only rectangular pulses were considered.

It is clear that the ultimate optimization of these parameters would require the

consideration of shape recognition as another variable of the problem. However, the added complexity of considering recognition goes beyond the scope of this research. Considering recognition at this point would require:

RG- Involving many more variables into the problem, e.g., learning, spatial frequency distribution of objects, masking, gray levels, modes of presentation, frame rate, movement of the camera, number of vibrators per unit area of skin tissue, etc.

RG- The experimental system, as designed for the sensitivity tests, will not permit these combinations of parameters primarily because of its multiplexing scheme, which limits it to duty cycles shorter than 1/16 (see section 3.8).

RG- Results for line recognition and first sensation thresholds for rectangular pulses of 250 Hz as a function of recovery time and number of pulses per burst are available [10, 15, 14]. These results suggest that the optimum for sensation threshold and line recognition threshold are close together. Thus, it could be expected that similar results would have been obtained for a line recognition and a sensitivity threshold test as a function of frequency and pulse width.

The study proposed here will show the optimum for the parameters of the waveform relative to sensitivity and power delivered. Trade offs depending on future research on recognition could be carried out by inspecting the combinations of parameters determined here.

4.3 Theoretical Analysis of the Stimulatory Waveform

The waveform designed to stimulate the tactile sense was presented in section 2.7 . It was composed of a stimulatory period, followed by a recovery period, as shown in Figure 10. The relevant parameters of the waveform for the stimulatory period are: pulse frequency, F , pulse width, W , amplitude, A , and number of pulses per burst, NPB . For the recovery period the relevant parameter is recovery time, RT .

Nunziata [10] studied the relationship between the number of pulses per burst and recovery time as it related to the sensitivity and power consumption using a 250 Hz rectangular waveform. The optimum combination for maximum sensitivity and minimum power delivered was 10 pulses per burst and 1 s recovery time. In the present study, only the parameters that modify the spectral distribution of the harmonics of the rectangular waveform will be considered. In addition, previous experiments [10] have shown that the sensitivity of the tactile sensation to NPB or RT is small in the vicinity of the optimum and there is some range around which a change in these parameters does not affect the output significantly.

Many previous systems to transfer information through the skin have used rectangular pulses as a driving waveform for the vibrators. Some have assumed that the best frequency for the rectangular waveform is 250 Hz [22, 5, 10, 14] because that is the optimum for sinusoidal waveforms. Others, without much explanation, have picked frequencies such as 60 Hz [31], 200 Hz [22] and 230 Hz [32, 33]. The frequency and pulse width of the rectangular waveform modify the spectral distribution of the harmonics of the fundamental frequency of the waveform [34, 35, 36]. As explained in section 4.2, different receptors will be targeted if different frequencies of stimula-

tion are used conjunctively. In that case, the overall tactile sensation produced by a rectangular waveform with harmonics distributed along the frequency spectrum, will be the response induced by the different types of mechanoreceptors¹ excited by that frequency distribution. Therefore, it is important to investigate the relationship of the parameters of the waveform that have an effect on the spectral distribution of the harmonics of the excitatory waveform relative to sensitivity and power consumption.

4.3.1 Spectral Analysis of the Stimulatory Waveform

The stimulatory waveform is composed of two periods: an stimulatory period followed by a recovery period. For this analysis the stimulatory waveform $S(t)$ will be assumed to be a periodic waveform². The Complex Fourier Spectrum for $S(t)$ can be calculated as:

$$F(nw_0) = \hat{F}_n(nw_0) \quad \text{for } -\infty \leq n \leq +\infty \quad (4.1)$$

$$F(nw_0) = \frac{1}{T} \int_T S(t) e^{-jnw_0 t} dt \quad \text{for } -\infty \leq n \leq +\infty \quad (4.2)$$

The relevant parameters of the stimulatory waveform, $S(t)$, will be denoted as follows: frequency of stimulatory cycle (f_0), frequency of the pulses during the stimulatory period (f), pulse width (W), number of pulses per burst (NPB), amplitude (A), recovery time (RT) and rectangular pulse shape. These parameters are shown in Figure 10.

The stimulatory period will be given by $T_s = (NPB - 1)\frac{1}{f} + W$. The total period of the waveform is $T_0 = \frac{1}{f_0} = T_s + RT$. The spectrum of $S(t)$ is given by

¹Different types of mechanoreceptors are tuned to different frequencies.

²This will be the case of a static presentation of shapes.

Figure 10: Stimulatory waveform, $S(t)$, is formed by a stimulatory period followed by a recovery period. The stimulatory period is formed by a burst of NPB rectangular pulses of pulse width W , amplitude A and pulse frequency f . The recovery period corresponds to a period of no stimulation RT .

$$F(nw_0) = \hat{F}_n(nw_0) \text{ for } -\infty \leq n \leq +\infty = \frac{1}{T} \int_T S(t) e^{-jn\omega_0 t} dt \text{ for } -\infty \leq n \leq +\infty,$$

where:

$$\begin{aligned} \hat{F}_n(nw_0) = \frac{1}{T_0} & \left[\int_0^W A e^{-jn2\pi f_0 t} dt + \int_{1/f}^{1/f+W} A e^{-jn2\pi f_0 t} dt + \dots \right. \\ & \left. \dots + \int_{\frac{NPB-1}{f}}^{\frac{NPB-1}{f}+W} A e^{-jn2\pi f_0 t} dt \right] \end{aligned} \quad (4.3)$$

$$\hat{F}_n(nw_0) = \frac{1}{T_0} \sum_{k=0}^{NPB-1} \int_{\frac{k}{f}}^{\frac{k}{f}+W} A e^{-jn2\pi f_0 t} dt \quad (4.4)$$

$$\hat{F}_n(nw_0) = \frac{1}{T_0} \sum_{k=0}^{NPB-1} \frac{A}{-jn2\pi f_0} (e^{-jn2\pi f_0 \frac{k}{f}}) (e^{-jn2\pi f_0 W} - 1) \quad (4.5)$$

$$\hat{F}_n(nw_0) = \frac{1}{T_0} \frac{A}{n\pi f_0} \left(\frac{e^{jn2\pi f_0 \frac{W}{2}} - e^{-jn2\pi f_0 \frac{W}{2}}}{2j} \right) e^{-jn2\pi f_0 \frac{W}{2}} \sum_{k=0}^{NPB-1} e^{-jn2\pi f_0 \frac{k}{f}} \quad (4.6)$$

$$\hat{F}_n(nw_0) = \frac{AW}{T_0} \text{sinc}(n2\pi f_0 \frac{W}{2}) e^{-jn2\pi f_0 \frac{W}{2}} \left(\sum_{k=0}^{NPB-1} e^{-jn2\pi f_0 \frac{k}{f}} \right) \quad (4.7)$$

and

$$\hat{F}_0 = \frac{AW}{T_0} NPB \quad (4.8)$$

with $T_0 = (NPB - 1) \frac{1}{f} + W + RT$.

Equation (4.7) shows that varying the pulse width causes the relative amplitude of the harmonics to change and that varying the pulse frequency, f , during the stimulatory period, causes the frequency distribution of the harmonics to change. Equation (4.7) can be used to generate Figures 11, 12 and 13, where the described result can be observed. In these figures, the amplitudes of the harmonics have been normalized. The maximum, which was assigned a value of 1, corresponds to the dc component for $F=50$ and $W=2$ ms. Figures 11 and 12 have the same pulse frequency of 50 Hz and, by reducing the pulse width from 2 ms to 1.3 ms, it can be seen that the relative amplitude of the fundamental and harmonics is modified. The frequency position of the first null is given by $\frac{1}{W} = \frac{1}{2 \times 10^{-3}} = 500$ Hz for the $W=2$ ms case and by $\frac{1}{W} = \frac{1}{2 \times 10^{-3}} = 750$ Hz for the $W=1.3$ ms case. Figure 13 shows that by changing the frequency of the stimulatory part of the waveform to 250 Hz, the whole spectral distribution of harmonics changed.

An additional factor of interest is that the response of the mechanoreceptors of the skin lies in the frequency range 25-1000 Hz, with a maximum sensitivity around 250

Figure 11: Frequency Spectrum for a stimulatory waveform with the following parameters: pulse frequency $f = 50$ Hz, pulse width $W = 2$ ms, amplitude $A = 1$, recovery time $RT = 1$ s, number of pulses per burst $NPB = 10$ and rectangular waveform.

Figure 12: Frequency Spectrum for a stimulatory waveform with the following parameters: pulse frequency $f = 50$ Hz, pulse width $W=1.3$ ms, amplitude $A=1$, recovery time $RT=1$ s, number of pulses per burst $NPB=10$ and rectangular waveform.

Figure 13: Frequency Spectrum for a stimulatory waveform with the following parameters: pulse frequency $f = 250$ Hz, pulse width $W = 0.4$ ms, amplitude $A = 1$, recovery time $RT = 1$ s, number of pulses per burst $NPB = 10$ and rectangular waveform.

Hz, as shown in Figure 2. This defines a window in frequency in which the receptors will respond and therefore defines a target window for the stimulatory waveform in which to excite response. In consequence, the relationship of the parameters of the stimulatory waveform, pulse width and pulse frequency, control the number and the amplitude of harmonics contributing to the tactile sensation. For high pulse frequencies, a smaller number of harmonics will fall within this frequency window. As the pulse width becomes smaller the harmonics spread toward higher frequencies of the spectrum. A discussion follows of the power delivered by or quadrature factor of the stimulatory waveform within the window of response for the mechanoreceptors.

4.4 Power Delivered or Quadratic Factor within the Frequency Window of Response for the Mechanoreceptors

The power delivered by the stimulatory waveform, within the window of response of the mechanoreceptors, can be calculated from equation (4.7). The average power delivered by the stimulatory waveform is given by: $Q_f = \frac{1}{T} \int_T f^2(t) dt = \sum_{-\infty}^{\infty} |\hat{F}_n|^2$. For a number of harmonics within a window of frequencies $Q_{fw} = 2 \sum_{N_1}^{N_2} |\hat{F}_n|^2$.

$$|\hat{F}_n|^2 = \left| \frac{AW}{T_0} \right|^2 \left| \text{sinc}\left(n2\pi f_0 \frac{W}{2}\right) \right|^2 \left| e^{-jn2\pi f_0 \frac{W}{2}} \right|^2 \left| \left(\sum_{k=0}^{NPB-1} e^{-jn2\pi f_0 \frac{k}{f}} \right) \right|^2 \quad (4.9)$$

$$|\hat{F}_n|^2 = \frac{A^2 W^2}{T_0^2} \text{sinc}^2\left(n2\pi f_0 \frac{W}{2}\right) \left| \sum_{k=0}^{NPB-1} \cos\left(n2\pi f_0 \frac{k}{f}\right) - j \sum_{k=0}^{NPB-1} \sin\left(n2\pi f_0 \frac{k}{f}\right) \right|^2 \quad (4.10)$$

$$|\hat{F}_n|^2 = \frac{A^2 W^2}{T_0^2} \text{sinc}^2(n 2\pi f_0 \frac{W}{2}) \left(\left(\sum_{k=0}^{NPB-1} \cos(n 2\pi f_0 \frac{k}{f}) \right)^2 + \left(\sum_{k=0}^{NPB-1} \sin(n 2\pi f_0 \frac{k}{f}) \right)^2 \right) \quad (4.11)$$

Therefore, the average power Q_{fw} delivered by the stimulatory waveform within the window of frequencies f_{wi} and f_{wf} is given by:

$$Q_{fw} = 2 \sum_{n=\frac{f_{wi}}{f_0}}^{\frac{f_{wf}}{f_0}} \frac{A^2 W^2}{T_0^2} \text{sinc}^2(n 2\pi f_0 \frac{W}{2}) \left(\left(\sum_{k=0}^{NPB-1} \cos(n 2\pi f_0 \frac{k}{f}) \right)^2 + \left(\sum_{k=0}^{NPB-1} \sin(n 2\pi f_0 \frac{k}{f}) \right)^2 \right) \quad (4.12)$$

Equation (4.12) makes it possible to study the relationship between the parameters of the stimulatory waveform; frequency and pulse width and the power delivered within a window of frequencies. Therefore, it is possible to study the relationship between the power within the window of frequencies and the sensitivity of the tactile sense to different combinations of frequency and pulse width.

Equation (4.12) does not consider the variation of sensitivity of the mechanoreceptors to the frequencies within the window (see section 2.3.4 for frequency response of the mechanoreceptors).

The frequency sensitivity or tuning of the mechanoreceptors can be represented mathematically by a window $W_f(nw_0)$, weighting the sensitivity of the tactile system to each frequency within the window. Therefore, the contributions of each frequency component of the stimulatory waveform, $F(nw_0)$, within the window of tuning, can

be weighted by $W_f(nw_0)$. Thus, the total power, $TPOW_w$ delivered by the stimulatory waveform within the window, weighting each frequency component by the relative sensitivity for tactile sensation can be calculated as:

$$TPOW_w = 2 \sum_{i=nmin}^{nmax} |F(nw_0)W_f(nw_0)|^2 \quad (4.13)$$

where $nmin$ is the lowest frequency component of the stimulatory waveform within the window, and $nmax$ is the highest frequency component within the window.

Therefore, in order to calculate the weighted power within the window it is necessary to determine $F(nw_0)$ and $W_f(nw_0)$. $F(nw_0)$ can be obtained from equation (4.12) and $W_f(nw_0)$ has been measured in the past [37, 29, 7]. Nevertheless, it was considered that determining the frequency response of the first sensation thresholds employing the transducer QMB-105 also would include any possible nonlinearities particular to this transducer in this frequency response range. Therefore the frequency response was measured using the QMB-105 and included in section 4.4.1.

4.4.1 Frequency Sensitivity for First Sensation Threshold

The frequency sensitivity response of the transducer/skin to sinusoidal excitation waveforms of various frequencies was measured. The transducer was excited with a sinusoidal waveform of different frequencies. The procedure followed was the same as described in section 4.6.3 for previous experimental threshold measurements. In accord with the frequency range of known sensitivity of the tactile system (see section 2.3.4 and section 4.6.2), responses to frequencies of 10, 25, 50, 100, 150, 200, 250, 300, 350, 400, 500, 600, 700, 800 and 1000 Hz were measured. The frequency of stimulation was randomly selected and presented to the subject, starting with zero amplitude. The amplitude was then increased by the subject until the first sensation

threshold was found. The sensitivity measurements were performed on the forearm, which is the same location selected for the experiments involving the stimulatory waveform (see section 4.6.3).

The window $W_f(nw_0)$ was constructed from the experimental results by normalizing the sensitivity curve so that the maximum sensitivity was one. The ratio between maximum and minimum sensitivity within the window was maintained constant before and after the normalization. Figure 14 shows the sensitivity within the window over which the mechanoreceptors are tuned.

4.4.2 Power Within the Window for the Mechanoreceptors

From equation (4.12), the power delivered by the stimulatory waveform weighted by the window of sensitivity of the mechanoreceptors can be calculated. Figure 15 shows the power within the window weighted by the sensitivity of the skin in a 3-D plot. The base plane's axes are pulse frequency and pulse width. It can be observed that the power increases as pulse width increases from 0.1 ms, until after the pulse width become larger than 50% of the period, when the power within the window decreases. The region where the power is zero is where the pulse width would be larger than the period and therefore has no realization.

Individual plots for frequencies of 25, 50, 100, and 200 Hz are shown in Figure 16 and b, and Figure 17 a and b. All these curves have similar shape, the power within the window increases until around 50% of the duty cycle and then decreases as the pulse width increases further. It can be observed also that as the frequency increases, the power in the window decreases.

Figure 14: Sensitivity to sinusoidal stimulation using the transducer QMB-105. The curve was normalized to provide a maximum sensitivity of 1.

Figure 15: Power delivered within the window of sensitivity for the skin. The power is presented as a function of pulse frequency and pulse width. The region represented by zeros is where the pulse width becomes larger than $1/F$ and therefore has no realization.

Figure 16: Power delivered within the window of sensitivity for the skin as a function of the pulse width. a) is for 25 Hz, b) for 50 Hz.

Figure 17: Power delivered within the window of sensitivity for the skin as a function of the pulse width. a) for 100 Hz and b) for 200 Hz.

4.4.3 Predicted Pulse Amplitude for Sensation Thresholds

Considering P_R to be the power required to reach threshold, P_Q the power in the pulse, and A the amplitude of the pulse;

$$P_R = A^2 P_Q \quad (4.14)$$

$$A = \frac{K}{\sqrt{P_Q}} \quad (4.15)$$

Therefore, equation (4.15) will predict the amplitude of the pulse when given the power delivered by the waveform. Figure 18 a and b, and Figure 19 a and b plots the amplitude A predicted from the theory for the same pulse frequencies of 25, 50, 100 and 200 Hz respectively. The prediction was that the sensitivity of the skin does not increase as a function of pulse width after the pulse width has reached a minimum width smaller than 1 ms. It also predicts that for very large pulse widths (close to the period given by the pulse frequency), the sensitivity will decrease.

4.5 Experimental Justification

In section 2.2 it was pointed out that with the current level of knowledge of the tactile system, given a stimulus, it is not possible from a theoretical analysis to determine the contributions of different mechanoreceptor types to a particular tactile sensation. The absence of such theory or model makes it impossible theoretically to predict the exact sensitivity to different excitatory waveforms based on the spectral analysis of the waveform. Nevertheless, experimental tools, through psychophysical experimentation, allow one to obtain a relationship between the excitatory waveform parameters and tactile sensation. These experimental results may contribute to the formulation of such a theory in the future.

Figure 18: Amplitude predicted for the pulse from the power within the window of sensitivity for the skin as a function of the pulse width. a) is for 25 Hz, b) for 50 Hz.

Figure 19: Amplitude predicted for the pulse from the power within the window of sensitivity for the skin as a function of the pulse width. a) for 100 Hz and b) for 200 Hz.

An experimental protocol was designed to determine the relationship between the pulse width and frequency of the stimulatory waveform and the sensation threshold excited by the stimulatory waveform.

4.6 Experimental Determination of Relationship between Frequency and Pulse Width of the Stimulatory Waveform versus Sensation Threshold

4.6.1 Introduction

The overall objective of this section is to find experimentally the optimal combination of the parameters, pulse frequency and pulse width, of the stimulatory waveform of Figure 10 which produce maximum sensitivity. To accomplish this objective, the psychophysical responses of human subjects to vibratory tactile stimulation of the skin were investigated. As detailed in section 4.2, past exploration of line recognition thresholds have yielded results similar to those for sensation thresholds [14, 10]. Thus, only first sensation threshold measurements were performed. The extrapolation to higher sensation levels is not direct, nevertheless Verrillo [29] showed that the sensitivity frequency response for different equal sensation levels corresponds to a family of curves with very similar U-type shape. Therefore, it can be expected that the extension of this study to other equal sensation levels will yield a similar combination of parameter values.

In the past, very little attention has been given to the parameter optimization problem when developing systems to transfer information to the visually handicapped through the tactile sense. This lack of parameter tuning has lead to systems requiring large amounts of power [1], limiting ability to miniaturize the electronic design and make the system portable. In the present work, the notion of space ³ is used to

³In the mathematical sense.

describe the sensitivity as a function of two parameters of the waveform: pulse frequency, F , and pulse width, W . Each point of the space is defined by the pairs of parameters (F, W) .

4.6.2 Experimental Design

In the experimental protocol of this research the whole space defined by the parameters, frequency and pulse width, within the frequency range of the mechanoreceptors was explored. Many preliminary experiments were performed to determine the size of the steps of exploration and the range for each of the variables determining the space. For this purpose sensation thresholds were measured on several volunteers. For a fixed frequency starting with very short pulse widths, e.g., 0.1 ms, the pulse width was increased until sensation threshold was reached with the maximum output current the system is able to provide, i.e., 120 mA. No consistent measurement of sensation thresholds was found for pulse widths smaller than 0.2 ms. For pulse widths larger than 0.2 ms, the sensation thresholds were very sensitive to variations in pulse width. It was found that a step of 0.1 ms was appropriate to describe sensitivity variations with respect to pulse width. After reaching a critical pulse width of about 1 ms, a fairly flat region for sensitivity versus pulse width was discovered. Thus the step in pulse width in this region could be larger. For very large pulse widths, i.e., when the pulse width was close to the period of the waveform ($1/F$), sensation thresholds again became very sensitive to pulse width and therefore a step of 0.1 ms was necessary to describe the variations of sensitivity versus pulse width. Therefore, the total range for pulse width was between 0.2 ms and $(1/F - 0.1)$ ms. According to the mechanoreceptors frequency response shown in Figure 2, the region of interest is for frequencies of 25-800 Hz. Since maximum sensitivity is ob-

tained around 250 Hz for sinusoidal stimulation and since the rectangular waveform spreads the frequency components toward the high frequency spectrum, the location of the optimum frequency of the rectangular waveform is expected to be shifted toward lower base pulse frequencies. Thus, more measurements were concentrated toward the lower part of the spectrum, i.e., below 300 Hz. Measurements were done at ten frequencies: 25, 50, 100, 150, 200, 250, 300, 400, 600 and 800 Hz.

In summary, the experiments consisted of determining the first sensation threshold for a set of 10 frequencies: 25, 50, 100, 150, 200, 250, 300, 400, 600 and 800 Hz. For each frequency the pulse width was varied from 0.2 ms up to $(1/F - 0.1\text{ms})$. The results of these experiments will permit the establishment of a complete picture of how the pulse frequency and pulse width parameters of the rectangular waveform affect the sensitivity.

4.6.3 Materials and Methods

Since the experimental exploration of the space defined by the parameters, pulse frequency and pulse width, requires many hours per experiment, the tests were performed only on three young sighted subjects (ages 23, 32 and 34). No significant difference in sensation threshold has been found in the past between young sighted and non-sighted subjects [14, 15]. Therefore, it is expected that these results can be extrapolated to a larger population without significant error.

Using the stimulatory waveform defined in section 2.7, experiments were performed to find the sensitivity of the skin to rectangular pulses while varying the frequency and the pulse width. The sensitivity to the stimulation is defined as the inverse of the stimulus intensity, i.e., the inverse of the peak current through the vibrator required to just reach sensation threshold. The optimum number of pulses

per burst was determined to be $NPB=10$ for a 250 Hz, rectangular waveform [10], this value was chosen for the present experiment.

The optimum recovery time from the sensitivity point of view was determined to be 1 s for a 250 Hz rectangular waveform [10]. Nevertheless, during preliminary experiments to determine the range and step for the frequency and pulse width performed for the present research (see section 4.6.2), it was difficult to measure consistently the sensation thresholds because the feedback to control the amplitude of the pulses was given only once a second. It was found that by shortening the recovery time to 0.5 s the feedback control was much more effective. Additionally a shorter recovery time, such as 0.5 s, provides a sampling time of roughly two frames per second, which in turn provides a better feedback when the subject is allowed to scan the environment with the camera to locate objects. Thus, in the present experiment the value for the recovery time was chosen to be 0.5 s. Obtaining an optimum frame rate must be determined in the future and involves at least a compromise among proper feedback to the user, power minimization and adaptation.

In section 4.6.2, the parameter space having F and W as variables was sampled in the ranges indicated, i.e., for frequencies of 25 to 800 Hz, and for pulse widths of from 0.2 ms to $(1/F - 0.1 \text{ ms})$. In preliminary experiments it was found that for a fixed frequency, as the pulse width is varied from 0 to $1/f$ the sensitivity at first increases as W increases from zero, then after the pulse width reaches a certain width of around 1 ms the sensitivity remains relatively constant, and finally the sensitivity decreases as it approaches $1/f$. The experimental measurements were concentrated on the areas of changing sensitivity and were spread evenly over the region of relatively constant sensitivity.

The parameters of the excitatory waveform that remained fixed during the whole

Table 3: Parameters of the stimulatory waveform for the experimental determination of sensitivity.

Fixed parameters for the experiment	
Recovery Time	0.5 s
Number of pulses per burst	10
Experimental controlled parameters	
Frequency	25 – 800 Hz
Pulse width	$0.2 - (1/f - 0.1)$ ms
Parameter controlled by subject	
Amplitude	0 – 130 mA

experiment were: recovery time, $RT = 0.5$ s, number of pulses per burst, $NPB=10$, and pulse shape = rectangular.

For the present experiment the variable parameters of the stimulatory waveform were: frequency (25-800 Hz), pulse width ($0.2-(1/f - 0.1)$ ms) and amplitude (0-130 mA peak). Table 3 shows the parameters of the stimulatory waveform and the values used for the experiment.

The microcomputerized system described in chapter III was used to produce the desired combinations of parameters for the stimulatory waveforms. The system was programmed to change the controllable parameters after the subject determined the sensation threshold for the previous set of parameters.

The subject was given control of the pulse amplitude of the stimulatory waveform. The test started when the amplitude was zero and the subject increased the amplitude until it reached sensation threshold. The variable parameter controlled by the subject was peak current, 0 - 130 mA.

Preliminary testing showed that threshold sensitivity results were similar for the

abdomen and the forearm [23]. The forearm was preferred to the abdomen because it was easier to control the position of the array on the arm than on the abdomen for the hours required for the experiment. The total duration of the experiment was approximately 8 hours per person and was performed in sequences of no more than 2 hrs at a time. After each set of measurements, which took around 20 min, the subject was allowed to rest for 5 minutes to minimize lack of concentration or numbness in the arm caused by the lack of movement. Each test sequence consisted of maintaining the vibratory stimulation at one fixed frequency while varying the pulse width randomly until the whole range was covered. The order in which different frequencies were tested was also random. Each measurement was repeated three times on different occasions and the maximum and minimum measured values of the set of three were discarded.

4.6.4 Experimental Results

In the first part of this section, the experimental results of the test of sensitivity as a function of pulse width for 10 different frequencies are presented. Next a graphical 3-dimensional plot of all the data collected is put together, from which, with the assistance of graphical techniques, an optimum can be chosen for sensitivity as a function of frequency and pulse width. The statistical significance of these results was established using standard ANOVA for repeated measures tests. A plot of sensitivity versus frequency was also constructed from the experimental data. The total power delivered by the stimulatory waveform for each combination of frequency and pulse width used in this experiment was plotted so that a trade off between sensitivity and power could be determined for each point determined by F and W . At the end of this section, plots of sensitivity versus frequency for different pulse widths are

presented.

Sensitivity as a Function of Pulse Width

The psychophysical response to vibrotactile stimulation was measured on 3 subjects employing an excitatory waveform composed of a stimulatory period followed by a recovery time. The subject controlled the amplitude of the excitatory waveform, increasing it until sensation threshold was reached. In each case the peak current required to produce sensation was measured and plotted for the average of the three subjects. The region of maximum sensitivity is that for which the required peak current is minimum.

Figures 20 through 29 show the peak current required to reach sensation for a single pulse frequency as a function of pulse width. The results represent the average $\pm$ one standard deviation for the three subjects. Each graph shows that for a very short pulse width, a large peak current is required to reach sensation, i.e., the sensitivity for very short pulses is not good. As the pulse widens, it reaches a region where the sensitivity does not increase with pulse width. At the other extreme, when the pulse width becomes almost as wide as the period of the waveform ⁴, the sensitivity decreases again, i.e., requires a larger peak current to reach sensation.

Table 4 shows a summary for each pulse frequency of: the pulse width range, the total number of measurements, the ranges of pulse width having the most variation in sensitivity, the number of measurements over the

⁴Close to the period of the waveform, $1/F$.

Table 4: Summary of ranges and number of measurements (mes) for each frequency.

Pulse Freq.	Range of Pulse Width	Total No. of mes	Range of W for most sensitivity variation in ms	No. of mes.	No. of mes. flat region
Hz	ms				
25	0.2-39.9	15	0.2-1 and 39.5-39.9	10	5
50	0.2-19.9	15	0.2-1 and 19.5-19.9	10	5
100	0.2-9.9	15	0.2-1 and 9.5-9.9	10	5
150	0.2-6.57	14	0.2-1 and 6.17-6.57	10	4
200	0.2-4.9	14	0.2-1 and 4.5-4.9	10	4
250	0.2-3.9	14	0.2-1 and 3.5-3.9	10	4
300	0.2-3.23	13	0.2-1 and 2.83-3.23	10	3
400	0.2-2.4	12	0.2-1 and 2.0-2.4	10	2
600	0.2-1.57	9	0.2-0.5 and 1.17-1.57	8	1
800	0.2-1.15	9	0.2-0.5 and 0.85-1.15	8	1

regions of most variation in sensitivity, and the number of measurements on the more or less flat region of the curves.

4.6.5 Sensitivity as a Function of Pulse Frequency

From the experimental data collected, it is possible to plot sensitivity versus pulse frequency. Figure 30 shows the peak current, the inverse of sensitivity, required to reach first sensation threshold as a function of pulse frequency. The plot is for a pulse width for which sensitivity is maximum, i.e., greater than 0.5 ms. Figure 30 shows that for low pulse frequencies, e.g., 25 Hz, the sensitivity is low; as the pulse frequency increases, the sensitivity increases to a maximum at around 100 Hz. If pulse frequency is increased above 100 Hz, the sensitivity decreases again. Sensitivity is minimum in the pulse frequency range between 300 and 600 Hz and

Figure 20: Peak current required to reach first sensation threshold for a pulse frequency of 25 Hz as a function of the pulse width of the stimulatory portion of the excitatory waveform. The pulse width varied from 0.2 to 39.9 ms as shown. The fixed parameters of the waveform were: recovery time $RT=0.5$ s, number of pulses per burst $NPB=10$ and pulse shape = rectangular.

Figure 21: Peak current required to reach first sensation threshold for a pulse frequency of 50 Hz as a function of the pulse width of the stimulatory portion of the excitatory waveform. The pulse width varied from 0.2 to 19.9 ms as shown. The fixed parameters of the waveform were: recovery time $RT=0.5$ s, number of pulses per burst $NPB=10$ and pulse shape = rectangular.

Figure 22: Peak current required to reach first sensation threshold for a pulse frequency of 100 Hz as a function of the pulse width of the stimulatory portion of the excitatory waveform. The pulse width varied from 0.2 to 9.9 ms as shown. The fixed parameters of the waveform were: recovery time $RT=0.5$ s, number of pulses per burst $NPB=10$ and pulse shape = rectangular.

Figure 23: Peak current required to reach first sensation threshold for a pulse frequency of 150 Hz as a function of the pulse width of the stimulatory portion of the excitatory waveform. The pulse width varied from 0.2 to 6.57 ms as shown. The fixed parameters of the waveform were: recovery time $RT=0.5$ s, number of pulses per burst $NPB=10$ and pulse shape = rectangular.

Figure 24: Peak current required to reach first sensation threshold for a pulse frequency of 200 Hz as a function of the pulse width of the stimulatory portion of the excitatory waveform. The pulse width varied from 0.2 to 4.9 ms as shown. The fixed parameters of the waveform were: recovery time $RT=0.5$ s, number of pulses per burst $NPB=10$ and pulse shape = rectangular.

Figure 25: Peak current required to reach first sensation threshold for a pulse frequency of 250 Hz as a function of the pulse width of the stimulatory portion of the excitatory waveform. The pulse width varied from 0.2 to 3.9 ms as shown. The fixed parameters of the waveform were: recovery time $RT=0.5$ s, number of pulses per burst $NPB=10$ and pulse shape = rectangular.

Figure 26: Peak current required to reach first sensation threshold for a pulse frequency of 300 Hz as a function of the pulse width of the stimulatory portion of the excitatory waveform. The pulse width varied from 0.2 to 3.23 ms as shown. The fixed parameters of the waveform were: recovery time $RT=0.5$ s, number of pulses per burst $NPB=10$ and pulse shape = rectangular.

Figure 27: Peak current required to reach first sensation threshold for a pulse frequency of 400 Hz as a function of the pulse width of the stimulatory portion of the excitatory waveform. The pulse width varied from 0.2 to 2.4 ms as shown. The fixed parameters of the waveform were: recovery time $RT=0.5$ s, number of pulses per burst $NPB=10$ and pulse shape = rectangular.

Figure 28: Peak current required to reach first sensation threshold for a pulse frequency of 600 Hz as a function of the pulse width of the stimulatory portion of the excitatory waveform. The pulse width varied from 0.2 to 1.57 ms as shown. The fixed parameters of the waveform were: recovery time $RT=0.5$ s, number of pulses per burst $NPB=10$ and pulse shape = rectangular.

Figure 29: Peak current required to reach first sensation threshold for a pulse frequency of 800 Hz as a function of the pulse width of the stimulatory portion of the excitatory waveform. The pulse width varied from 0.2 to 1.15 ms as shown. The fixed parameters of the waveform were: recovery time $RT=0.5$ s, number of pulses per burst $NPB=10$ and pulse shape = rectangular.

Figure 30: Peak current required to reach first sensation threshold as a function of pulse frequency for a pulse width greater than 0.5 ms, i.e., in the region of maximum sensitivity.

improves somewhat toward 800 Hz.

4.6.6 3-D Plotting of Experimental Results

The experimental results presented in the previous section can be summarized in a 3-D plot which permits a comprehensive view of how sensitivity is affected by changes of the parameters of the stimulatory waveform pulse frequency and pulse width. Figure 31 shows the peak current required to excite tactile sensation for pulse frequencies of 25, 50, 100, 150, 200, 250, 300, 400, 600, 800 Hz and for pulse

width from 0.2 to 39.9 ms with a step of 0.1 ms. The steps in the pulse width axis were obtained by linear interpolation between the experimental points shown in the previous section. The region represented by zero amplitude of peak current is where the pulse width becomes larger than $1/F$ and therefore has no realization. The maximum sensitivity is found at about 100 Hz with pulse widths of 0.5 or 1 ms. To excite sensation threshold with a pulse frequency of 100 Hz, requires only 63% of the peak current required to excite sensation threshold with a pulse frequency of 250 Hz. Thus, the result indicates that from the sensitivity point of view, a pulse frequency lower than 250 Hz requires less power to reach sensation than the 250 Hz pulse. The shortest pulse width that excites maximum tactile sensitivity, for all the frequencies tested, was in the range 0.5 - 1 ms. From the power consumption point of view, the shorter the pulse width the better, therefore in this study 0.5 ms was selected as the shortest pulse width that will elicit sensation with minimum stimulus amplitude.

4.6.7 Statistical Significance of the Experimental Results

Statistical analysis of the experimental data was performed in order to determine the significance of the measured variations on the sensation thresholds for each frequency as a function of the pulse width. ANOVA analysis ⁵ for repeated measures show that the sensation threshold results are "very highly significant" [38] ($p < 0.001$) for frequencies of 25, 50, 150, 200, 300, 400 and 800 Hz, that the results are "highly significant" ($0.001 < p < 0.01$) for frequencies of 100 and 250 Hz, and that the results are "significant" ($p < 0.05$) for 600 Hz.

⁵Analysis of variance.

Figure 31: First sensation thresholds: Peak current required to reach sensation threshold as a function of the pulse width of the stimulatory portion of the waveform for the pulse frequencies of 25, 50, 100, 150, 200, 250, 300, 400, 600 and 800 Hz. The fixed parameters of the waveform were: recovery time $RT=0.5$ s, number of pulses per burst $NPB=10$ and pulse shape = rectangular waveform.

4.7 Total Power Delivered by or Quadratic Factor of the Stimulatory Waveform as a Function of Pulse Width

The total average Quadratic Factor (proportional to power) per cycle delivered by the stimulatory waveform is given by $Q_T = \frac{1}{T} \int_T S(t)^2 dt$

$$Q_T = A^2 \frac{W(NPB)}{(NPB - 1)\frac{1}{f} + W + RT} \quad (4.16)$$

Figure 32 shows the total quadratic factor per cycle delivered by the stimulatory waveform as a function of pulse width of the stimulatory portion of the waveform for the 10 frequencies used in the experiments. The following were the fixed parameters of the waveform: recovery time $RT=0.5$ s, number of pulses per burst $NPB=10$ and pulse shape = rectangular waveform. Each curve for a different pulse frequency ends at a maximum pulse width of $1/f$ and therefore for higher frequencies the maximum pulse width is shorter than that for lower frequencies. It can be seen that the shorter the pulse width at any pulse frequency, the smaller the power delivered by the stimulatory waveform. It can also be observed that for a fixed pulse width, the power delivered per cycle increases as pulse frequency increases. Therefore, from only the perspective of power consumption, the shorter the pulse width and the lower the pulse frequency, the smaller the power delivered by the stimulatory waveform.

The total power consumption per cycle can be shown in a 3-D plot as a function of pulse frequency and pulse width as depicted in Figure 33. The x and y coordinates represent pulse frequency and pulse width and the z axis represents the power delivered by the waveform. In this figure the dependence of power upon pulse frequency and pulse width can be better appreciated and permits the determination of the power delivered by any possible combination of pulse frequency and pulse width.

Figure 32: Total power per cycle delivered by the stimulatory waveform as a function of the pulse width of the stimulatory portion of the waveform for the pulse frequencies of 25, 50, 100, 150, 200, 250, 300, 400, 600 and 800 Hz. The fixed parameters of the waveform were: recovery time $RT=0.5$ s, number of pulses per burst $NPB=10$ and pulse shape = rectangular waveform.

Figure 33: Total power per cycle delivered by the stimulatory waveform as a function of the pulse frequency and pulse width of the stimulatory portion of the waveform. Pulse frequency and pulse width cover the whole range where the tactile receptors are tuned. The fixed parameters of the waveform were: recovery time $RT=0.5$ s, number of pulses per burst $NPB=10$ and pulse shape = rectangular waveform.

4.8 Summary

The results of this experimental work permit the exploration of the space generated by the parameters pulse frequency and pulse width of the stimulatory waveform for sensitivity and power delivered and the determination at any point of the relative trade off between sensitivity and power delivered. The fixed parameters considered in this analysis were number of pulses per burst =10 and recovery time = 0.5 s.

Figure 34 (a) shows the total power delivered in a magnified view for the region of interest below 1 ms pulse width. As pulse frequency or pulse width increases, more power is delivered. In part (b) of the figure, a magnification of the 3-D sensitivity curves is provided for the region between 25 and 200 Hz and for pulse widths between 0.2 and 12.5 ms.

Referring to the optimum value, the maximum sensitivity and minimum power consumption are obtained for a pulse frequency of about 100 Hz and a pulse width of .5 ms.

(a)

(b)

Figure 34: (a) Shows the total power delivered as a function of pulse widths in the region for pulse widths between 0.1 and 1 ms. (b) Shows an amplification of the 3-D sensitivity curves between 25 and 250 Hz and 0.2 and 12.5.

CHAPTER V

CONCLUSIONS

Two major areas of investigation were addressed in this research: (1) The design and development of an experimental system with programming control capable of transforming optical images into tactile pictures with reduced hardware compared to previous attempts; and (2) the optimization of the relationship between the parameters of the driving waveform used to excite the electro-mechanical transducers, to maximize skin sensitivity and minimize power delivered to the transducers.

The system designed is capable of acquiring a 256x256 pixel image and producing a vibrotactile output picture of 16x16 with four levels of gray. The system meets all the design constraints of maximum peak current, size reduction, linear amplification channels, number of pulses per burst, pulse frequency, pulse width and recovery time. The maximum frame rate for the system is 2.8 per second.

The size of the system was reduced by roughly a factor of 16 by the use of multiplexing techniques. Groups of 16 transducers share the use of lines and amplifiers by multiplexing the signal in time. The total number of lines connecting the system to the array of transducers was reduced from 257 to 22.

The multiplexing scheme has the added advantage of reducing the instantaneous peak power requirements to 1/16 of that required by parallel implementation. The power reduction relative to systems that use 50 % duty cycle and continuous stimulation was computed. For a 100 Hz rectangular stimulatory waveform with a recovery time of 0.5 s, pulse width of 0.5 ms and 10 pulses per burst, the reduction of average

power consumption per cycle relative to the same 100 Hz continuous rectangular waveform with 50 % duty cycle, was by a factor of 60.

The system provides the capability of investigating of the relationships between the parameters of the driving waveform on sensitivity and power consumption. As stated in the specifications of the system, the number of pulses per burst can be varied between 1-20, the pulse width between 0.1 and 40 ms, the frequency between 25 and 800 Hz, the recovery time between 0.5 and 1.5 s.

Perhaps the most significant contribution of this work is that a theory was developed to predict pulse amplitudes required for sensation thresholds based on the power delivered by the excitatory waveform within the 'window of sensitivity' of the mechanoreceptors. It was found that the theoretical predictions almost perfectly fit the experimental data. The importance of this finding is that it clarifies a controversy in the field: in the past it has been proposed that power delivered by different waveforms is not related to the mechanoreceptor response because the lack of correlation found between total power delivered and sensation threshold. The theory proposed here and the experimental data gathered show that it is not the total power delivered by the waveform that governs sensation thresholds, but the power delivered within the 'window of sensitivity' of the mechanoreceptors.

The optimization with respect to sensitivity and power of the parameters of the driving waveform, pulse frequency and pulse width, resulted in the optimum combination: a pulse frequency of 100 Hz and a pulse width of 0.5 ms.

Other studies on the parameters of the waveform and modes of presentation should be conducted before a final prototype is designed. The maximum frame rate should be optimized to maximize the recognition of moving objects, while minimizing power consumption. This study would be important when considering the system

for use as a mobility aid for the visually handicapped. From the information transfer perspective it would be desirable to have the fastest frame rate possible, from the power consumption perspective the frame rate should be as low as possible. As the frame rate increases, the recovery time becomes shorter and adaptation becomes greater, requiring more power to reach sensation. The faster the frame rate, the better the feedback for moving object tracking. There are limits also on the maximum frame rate to avoid masking between two successive patterns presented to the tactile system. Craig [24] found that masking was avoided when presenting letters to the finger with an interstimulus interval larger than 200 ms. Therefore, from this perspective the maximum frame rate should be limited to no more than 4 per second. It has also been determined that for letter recognition using the Optacon, a minimum display time greater than 40 ms is required [39]. The stimulatory waveform designed in this research possesses a display time of 100 ms and interstimulus interval of 500 ms. Both satisfy the letter recognition criteria found in [24, 22].

A sensitivity, power optimization study should be carried out with the shaped pulse and determine if savings in power and reduction in audible noise are possible.

The shape of the 'window' within which the burst of pulses occurs should be optimized. For the present study that 'window' was rectangular, allowing the onset and end of the burst to be abrupt. This window could instead be shaped for maximum sensitivity and minimum power consumption.

Multiple tests regarding modes of presentation and recognition should be performed in the future. It should be determined whether scanning or scripting have an effect on recognition. Image processing enhancements, such as outlining and inverse mode, should also be investigated.

Finally, research on the transducers is most critical to find smaller devices that

consume less power with less weight at a low cost. It is important to first reduce the size of the array because the 20 cm x 20 cm matrix is hard to fit on thin people. From the wearability point of view it would also be desirable to build a smaller, lighter array. From the research point of view, by reducing the size of the transducers, tests designed to determine the maximum spatial resolution for tactile displays could be performed.

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