Automatic Visual to Tactile Translation, Part I: Human Factors, Access Methods and Image Manipulation

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Abstract— **This is the first part of a two-part paper that motivates and evaluates a method for the automatic conversion of images from visual to tactile form. In this part, a broad-ranging background is provided in the areas of human factors, including the human sensory system, tactual perception and blindness, access technology for tactile graphics production, and image processing techniques and their appropriateness to tactile image creation. In Part II, this background is applied in the development of the TACTile Image Creation System (TACTICS), a prototype for an automatic visual-to-tactile translator. The results of an experimental evaluation are then presented and discussed, and possible future work in this area is outlined.**

Keywords— **blindness, image processing, microcapsule paper, tactile graphics, tactile imaging**

I. Introduction

ACCESS to visual information can widen the avenues of professional and social interaction for blind persons. This is often accomplished through a manual process that translates a visual representation into a corresponding tactile form. Involvement of a sighted person in this conversion step generally is necessary, however, limiting the autonomy of the blind person. Further, this conversion is a time-consuming effort involving the use of glue, string, scissors, cardboard and other craft materials, tracing paper and marking pens, or computer-aided drawing packages to produce a tangible representation of the original image. Although worthwhile, such an approach is neither timely nor easily reproducible, and clearly necessitates the involvement of a specially skilled sighted individual in the process.

Computers excel at displaying information via multiple media, including the CDROM and ubiquitous Internet. The omnipresence of the computer in everyday life provides ready availability to a myriad of graphical, textual and auditory information for sighted and blind individuals alike. For blind computer users, text-based information is output as synthesized speech or as braille via a special purpose printer or display. The surging prevalence of the graphical user interface (GUI), however, introduces severe impediments for the blind community. Pictures, drawings, video and animation are not directly accessible to the blind computer user.

The sense of touch is relied upon frequently by blind persons in lieu of sight. One common method of presenting visual images in a touchable or tactile fashion is through use of *tactile graphics* [49]. Tactile graphics provide a raised representation of such visually useful materials as maps, graphs and other simple drawings. By current practice, these are prepared by a sighted person individually and by hand. This preparation is neither timely nor efficient. Timeliness, while not a major issue for infrequently changing items, such as maps, is a consideration for the large volume of frequently changing visual information [20], such as that available via the Internet and from other sources.

Tactile imaging is the process of turning a visual item, such as a picture, into a touchable raised version of the image so that this tactile rendition faithfully represents the original information. Properly done, tactile imaging provides access for blind persons to visual information that is inaccessible via other means such as audio or textual description. *Tactual perception*, the physiological capabilities of the human sensory system to explore and discern via the sense of touch, is well understood. Factors such as the size and shape of the fingertip, temporal and spatial response of the nerve receptors in the skin, and incorporation of kinesthetic, or haptic, cues must be considered. These factors limit the size and detail of tactile images to within the response ranges of these various factors [49], [72].

The way in which the mind perceives and classifies images is a well-studied area, one in which a number of theories have developed. Among these, perhaps the most accepted view is that of human memory being arranged hierarchically from general to specific in terms of one or more qualities of the object being perceived. Whether the information is visual or tactile, the brain uses this same general framework for classification [14], [36], [40]. Thus, producing usable tactile images from photographs is a challenge requiring a careful balance of resolution, size, shape and detail. Having too much detail in a tactile image will result in much of its content being lost, actually degrading its clarity and utility due to an information overload of sorts. This overload results from limitations of tactual perception, particularly the physiological disparity between the resolution of the human eye and fingertip. Including too little detail will result in a tactile image that may not feel like anything more than a simple shape, not adequately representing the original image at all [37]. This ambiguity is due to the manner in which the brain categorizes what it perceives, in this case classifying tactually indistinguishable items as the same, even though the unprocessed visual originals may have been quite different.

This two-part paper explores the possibility of automatically converting some forms of visual information into tactile information. The means for testing this idea is the development of a composite software/hardware system for automatic translation of electronic images into tactile form. In this system, an aggregate process comprised of a sequence of image processing algorithms is applied to an image to produce a simplified version of the original. This caricaturized image is subsequently output in a raised tactile graphic form on microcapsule paper, suitable for display to a blind person.

In the first part, topics in tactual perception, the human sensory system in general, tactile graphics production and image processing are examined. To provide access to visual information for blind persons, an understanding of how we, as humans, interface with the world around us is vital. Perception at the tactual and mental levels and related human performance parameters are discussed, and the visual and tactual senses are contrasted. Relevant statistics regarding the blind population are presented, and an overview of blind computer user interface technology is provided. The techniques for tactile graphic production are reviewed, as is current research in this area. Cumulatively, this background propels a further discussion of image processing algorithms that can assist in the perception of information that is converted from visual to tactual. This broad array of background information is provided to justify a heretofore unexplored combination of factors and theories from these areas, all of which play formative and vital roles in the motivation of this research.

Presented in the second part is an evaluation of the TACTile Image Creation System (TACTICS) [85], [86], which attempts the automatic conversion of images from visual to tactile. This prototype system provides access to previously inaccessible visual information using image processing and tactile graphics production techniques. The goal of this system is to free the blind computer user from reliance upon a sighted individual to prepare custom tactile graphics, or *tactics* [25], and to overcome the considerable time delay in doing so. The specific techniques used in this system are introduced and support is provided linking their use to applicable theories of perception. The efficacy of these techniques, which involve the application of a number of image processing algorithms in various combination and sequences, is evaluated in terms of discriminability, identifiability and comprehensibility as measured in a series of experiments. The results of these experiments are analyzed for significance, and anecdotal evidence is added to support a discussion of their potential import. Finally, future directions in which this work may lead are outlined.

II. HUMAN FACTORS

The efficacy of a method for automatically converting visual information into tactile information necessarily is dependent upon a variety of factors, which are reviewed in this section. To guide the design of such a system, an understanding of the human factors of sensation and perception, including how the sense of touch compares to the sense of sight, is important. There are lessons to be learned from past and current techniques for tactile graphic production and other non-visual methods used by blind persons to access computer-based information. The medium for the description of visual information that is under consideration in this paper is the computerized image. How such images are represented and the techniques that can be used to operate upon them are explored, and their correspondence to human tactual perception is considered. The background[1] provided in this section will be used to motivate the prototype system and experimental protocol detailed later.

A. The Human Sensory System

The fundamental issue in presenting visual information in a meaningful tactile form is the understanding of some basics of human sensory perception. By reviewing how the human sensory system collects and comprehends information and what the limits are to the type and amount of information the senses can process, it may be possible to identify factors that can play a role in the conversion of information intended for one sense to a form suitable for another sense.

Humans receive all of their information about the world around them using one or more of five senses [14]. The *Gustatory Sense* provides information on taste qualities such as sweet, salty, sour and bitter. Often working in conjunction with taste is the *Olfactory Sense*, which provides smell information. The *Auditory Sense*, our hearing, allows us to receive auditory information such as music, speech and noise. The *Tactual Sense* is comprised of touch and kinesthesis, providing information about such physical world qualities as temperature, perception of texture, position and motion. Finally, the *Visual Sense*, our sense of sight, is how we receive visual information including color, brightness, depth of field, and motion.

The *bandwidth* of a sense refers to the capacity of that sense to receive and perceive information. Studies show that vision, as one might intuitively expect, is our highest bandwidth sense, followed by hearing and touch (Table I[2]) [39]. The Visual Sense is two orders of magnitude better at carrying information than the Auditory Sense, which is two orders of magnitude better than the Tactual Sense.

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[1] See Table III for a summary of various parameters related to tactual perception and that affected the design of TACTICS.

[2] Table I states that the human fingertip processes vibrotactile signals at a rate of 10^2 *bits/sec*. The results of previous research indicate

The Gustatory and Olfactory Senses are much more prone than the others to the effects of *adaptation*, and are not efficient at carrying information at a rate anywhere near that of even the Tactual Sense. *Adaptation* refers to the tendency of a sense to grow accustomed to a stimulus, thereby becoming less sensitive to it over time. Taste and smell are prone to adaptation and have comparatively slow recovery times, while the other three senses have speedier recovery times that are roughly proportional to their bandwidths. As the highest bandwidth and most resilient sense, vision is arguably of the greatest importance among the senses, and therefore the hardest to do without. By comparison, the other senses have lower to much lower information capacities which makes the problem of sensory substitution for vision a difficult one to address [14], [37].

The implications for development of a vision substitution system are significant by virtue of this large bandwidth disparity. Visual information cannot simply be mapped directly to the auditory or tactual domains, but clearly must be reduced by some bandwidth correlated scaling factor. Further, this scaling must preserve the meaning of the original visual information to be useful.

B. *Tactual Perception*

Tactual perception primarily refers to active exploratory and manipulative touch. Study of the physiological factors involved in tactual perception is important if one is to gain an understanding of how best to create tactile images. For a tactile image to be useful, a blind person must be able to explore it with the sense of touch, usually the fingers, and extract some content information. Thus, limits to tactual perception, such as resolution of the human fingertip, image scale as a factor of comprehension, and how the mind processes such information are important considerations [48], [49].

The basic physiology of the human skin defines limits to the ability of our sense of touch. Of particular importance to tactile graphics are the difference limen and its relation to temporal response thresholds and masking phenomena. The *difference limen* is the minimum statically discernible displacement between two points such that the points are distinct. In effect, this is tactile resolution, which for the skin of the fingertip is approximately 2.5mm. When statically felt, two points closer than this distance tend to feel like one point, whereas two points farther apart than this feel like two distinct points [72]. This figure indicates that the resolution of the fingertip is much lower than the human eye. Therefore, we can safely say that tactile images require lower resolution than visual images. The definitive work on this two-point threshold, including its use as an indicator of the relative spatial resolution as a function of body locus, is in [87].

Spatial sensing incorporates what we know about static sensing, embellished with further measurements of sensory abilities taken during motion of the finger [70]. Related to the two-point difference limen is the minimum discernible displacement of a point on a surface. For highly smooth surfaces and under carefully controlled laboratory conditions, a 2-micron high point can be felt using active touch [44]. The height of a braille dot, an easily discernible object, is in the range 0.02 - 0.05cm [21]. This is a generally acceptable range of heights for tactile graphics, with heights at the upper end of the range naturally providing relative improvements in perceptibility [49], much as brighter lighting or higher volume can, to a point, improve perceptability in the visual and auditory domains. The limiting factor for the height of tactile graphics is inherent in the media in which they are produced.

Spatial tactile discrimination has been measured using square-wave gratings of varying groove amplitudes and separations under conditions of active exploration [33], [49], [72]. Sequences of gratings were presented to the distal pad of the right index finger in both the same and orthogonal orientations to the axis of the finger. Observers noted differences in orientation of the grooves, which revealed the distance at which orientation of grooves became indiscriminable. This study demonstrated that the minimum tactually discernible grating resolution is 1.0mm, and that such discrimination improves linearly as the grating width increases above 1.0mm. This result is due to the forward masking effect of one stimulus upon perception of subsequent stimuli. The cutaneous receptors in the skin require a period of time to recover after cessation of one stimulus before correct sensing of a subsequent stimulus can begin [48].

Taken together, these factors appear to indicate that the resolution of a tactile image should be somewhat finer than 1 *dot/mm* to produce a relatively smooth feel to the image, while resolutions much lower than this seem to provide little or no benefit to tactile perceptibility. For comparison, a resolution of 1 *dot/mm* equals 25.4 *dots/inch*, and the resolution of a standard laser printer is at least as fine as 300 *dots/inch*.

C. *Tactile Pattern Perception*

The visual sense responds well to minute differences in stimulus, while the sense of touch tends to need greater variation in stimulus patterns to succeed in perceptual tasks [38], [49]. Although touch can discriminate and recognize complex tactile patterns [37], such perception involves a number of complicated cognitive processes [41].

There is strong basis for the supposition that spatial information, which includes graphics, is stored in the visual cortex portion of the brain [40]. This mechanism is similar for sighted and blind persons, regardless of whether this information is gathered using the sense of sight or touch. Research indicates that the ability to store and subsequently retrieve tactually perceived spatial information can vary greatly from individual to individual. This variation depends to a significant degree on the level of *visual memory* a blind person possesses, as often determined by the age of the onset of blindness. There is comparatively little variation in such ability among the sighted population [67]. The storage and retrieval of spatial information is believed to be

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this rate to be no more than 10^1 $bits/sec$ [15], [26], [42].

organized in a hierarchical fashion in the brain, which classifies information based on gross characteristics first, followed by detailed characteristics [6], [80]. Although the resolution of the sense of touch degrades slowly with age [61], which unfortunately equates with a statistical rise in blindness [67], [69], experience with tactile graphics can make up for this slight loss of touch sensitivity [37], [84].

The method typically used by a blind person to explore a tactile graphic tends to support the hierarchical view of human spatial memory. The exploration by a blind person of a tactile graphic generally is performed in two stages. First, the entire image is explored as a whole, providing a general tactile overview. Second, the details of the tactile image are explored. Research has verified this methodology [29] and has shown that this technique is used by blindfolded sighted persons as well. These results indicate that the concept of a hierarchical structure of the human spatial memory is a reasonable assumption.

It is important to note that the acuity of the touch sense is comparable to blurred vision in similar tasks [1], [47]. The significance of this relationship is that any tactile representation of visual information, based on what we already know about tactual perception, should be sufficiently simple to make up for this reduced level of acuity [16], [20], [49], [72]. This result supports our choice of pursuing methods of image simplification in producing tactile images from their visual counterparts.

D. Aiding Comprehension

Comprehension of a tactile display is increased when the reader is somehow clued in to what will be felt [20]. Just as one expects photographs in a newspaper to have an associated caption, so too would one reasonably expect that the comprehensibility of a tactile image would be enhanced by including some associated textual information. This enhancement can be accomplished using standard techniques, such as by incorporating braille text with an image or by using speech output from a computer speech synthesizer to add information and increase comprehension.

In a photograph, information about the relative depth within the field of view of objects is provided by masking, shadows and size [14], [40]. This information is not readily discernible in a tactile format and is a factor which can inhibit the comprehensibility of a tactile image. One surprising side effect of *congenital blindness* on comprehension is the relative insensitivity to orientation of the tactile graphic being touched. Where blindfolded sighted subjects in one study were confused by a rotated or non-upright tactile graphic representation of a known object, blind subjects suffered little confusion. These blind subjects were quite facile at mentally rotating the spatial information perceived from the graphic representation, performing much better at comprehension tasks than the sighted subjects under the same conditions [12].

Representing depth and perspective in a tactile image is difficult, if not impossible, using a two-dimensional tactile display medium. Further, the congenitally blind individual lacks a visual frame of reference for interpretation of such inherently three-dimensional information when it is mapped onto a two-dimensional display [49].

E. The Blind Population

The American Foundation for the Blind recommends that the term *blind* be reserved for individuals with no usable sight whatsoever, while *low vision*, *visually impaired* or *partially sighted* can be used to describe those with some usable vision. These terms coincide with standard medical diagnostic guidelines which divide visual impairment into two classifications: *no light perception* (NLP) and *light perception* (LP). An individual with corrected visual acuity of 20/200 in the better eye or a visual field of 20 degrees or less in the better eye is considered *legally blind*. A blind person is either *congenitally blind*, being blind from birth or during the first five years of life and possibly lacking visual memory, or *adventitiously blind*, with blindness beginning after the age five and with the probable presence of visual memory. *Visual memory* means the ability to classify and remember objects we perceive in terms of visual characteristics, such as shape, size, color, position and perspective [67].

There exist numerous misconceptions regarding blind persons [31], [53], [67]. Positive misconceptions are that blind people are exceptionally musical, possess extraordinary senses of hearing and touch, and are highly intelligent. Negative misconceptions include suppositions of helplessness, dependence, laziness and lack of intelligence. Of particular relevance is the supposed increased sense of touch. Touch sensitivity varies little from person to person, with no statistical difference between the sighted and blind population [50]. However, it does seem reasonable that a blind person may be more accustomed to relying on the sense of touch and interpreting tactual information [3], [37].

Statistics released by the World Health Organization in 1987 estimate that there are 30- to 40-million blind people in the world [67]. According to 1989 statistics from the National Society to Prevent Blindness, approximately 500,000 U.S. residents are legally blind [67]. Of those figures, roughly ten percent are totally without sight [69].

The increase in the general population's reliance upon the computer carries over to the blind population as well [8]. As the number of computer users continues to grow quite rapidly, any precise count of users would obviously be out of date even before it was written down. However, what is certain is that this number is sufficiently large to support an assertion that blind computer users make up a sizable group. It is worth noting that the availability and affordability of synthetic speech output via computer has broadened access to information for this population as compared to braille access to the same information.

According to the American Printing House for the Blind (APH), of the blind population residing in the United States and of reading age, fewer than 16 percent are fluent in braille, while worldwide the figure is lower still [84]. Another study cites the braille fluency rate among blind and visually impaired computer users at 10 percent [27]. While these low braille literacy rates are discouraging, there is some reason for optimism in the future. In a study of school systems for blind children, more than one third of the students were found to be fluent in braille, although audio output, either in the form of recorded books or speech synthesis, was still the mode of choice at the time of the study (Table II[3]) [84], [90].

III. Access Technology for Blind Computer Users

Blind persons have a great many means for accessing textual and visual information [7], [10], [11], [13], [19], [20], [25], [24], [27], [43], [54], [78]. A number of these methods already do or can be adapted to provide blind computer users with access to graphical information. Many traditional methods of access, such as braille output in one form or another, are, and continue to be, widely used. Their efficacy is unquestioned. Some relatively recent developments, such as speech output, are also effective and quickly merging with traditional methods to create new standards for access. Research is active in the development of dynamic and refreshable tactile displays [11], [19]. Innovations in the materials and techniques used to display visual information in a non-visual fashion are achieving some success [22], [82]. These new methods show promise, although technology continues to lag behind concept.

The task of accessing visual information is one of mapping information from the visual domain to that of one of the other senses. Knowing that this is essentially an information volume-reduction problem, given that the bandwidth of each of the other four senses is significantly lower than that of vision, it is helpful to look at some of the more successful approaches to tackling this problem before developing additional solutions. These methods fall into the general categories of *Static Tactile Graphics*, *Auditory Interfaces*, *Dynamic Tactile Graphics* and *Haptic Interfaces*. In addition to these available means, there is active research in this area that is worth reviewing as well.

A. Static Tactile Graphics

Methods for production of static tactile graphics are varied and usually require the intervention of a sighted person in their preparation [20], [78]. The process of converting computer graphics to tactile graphics can be a labor-intensive and time-consuming one. There are three important steps in this process: (1) *editing*, (2) *transferral* and (3) *production*. Consider any original two-dimensional graphic, such as a pencil sketch, ink drawing, graph, diagram, illustration or printed picture.

For a tactile graphic display to be comprehensible, it must not contain too much information. General design guidelines, developed through years of practical application and refinement of technique, suggest that a tactile graphic should contain the least amount of information possible to convey successfully the content of the image. Clutter or an overabundance of detail in a tactile image can detract from its usability and hamper one's ability to understand its content [38], [49]. Thus, it is important to simplify complex images in the *editing* step of the process of converting them to tactile images. Experience shows that a tactile graphic that is too large or too small detracts from comprehensibility as well [89]. The size of a tactile image should be kept within a hand span, or roughly 3in to 5in on a side.

Transferral entails placing the image onto some tactile output medium. A picture is first traced on tracing paper, and then is transferred to the tactile display material using carbon paper and retracing. Other methods for transferral include the *pantograph*, which is an instrument consisting of four arms jointed in parallelogram form. It is adjustable to produce tracings of smaller, the same, or larger sizes. Using grids to scale images is also a common technique, as is use of the enlargement capabilities of modern photocopier machines.

The *production* step is where the physical tactile graphic is produced. There are numerous methods considered standard; without exception, all require the intervention of a sighted person to translate a visual image into a tactile one. There are a number of commonly used methods for tactile graphic production [19], [20], [78], including the following:

Raised-line drawing boards: Designed to be used by blind persons for producing raised-line drawings, this common tool is also useful for fast production of tactile versions of visual originals. A stylus produces a raised line when drawn over a plastic film, giving an instant tactile representation.

Tactile-experience pictures: This method is often used for young children. Pictures are constructed of a variety of materials, including wood, plastic, cloth, sandpaper, fur, and metal, which are glued to a stiff cardboard backing. This method involves individually fashioning each piece out of the desired material and assembling the resulting pieces into the tactile picture.

Buildup displays: Similar in method to tactile-experience pictures, buildup displays rely on multiple layers of paper to build up a raised drawing. Additional materials, such as wire, string and even staples, may be added to enhance the drawing.

Embossed paper displays: This technique reproduces a drawing on heavy paper using a collection of embossing tools. A reverse view of a sketch is first transferred to the back of a sheet of embossing paper. The tools are then used to trace the sketch, embossing it as a series of raised dots.

Braille graphics: Graphics embossing can be produced more simply and speedily using a standard braille printer connected to a computer. Operating in graphics mode, the printer maps *pixels* of the original image to braille dots to produce the embossed version of the picture. The resolution of this method is low, and to be effective, the original image must be a simple line drawing. This method has two distinct advantages: many blind computer users have

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[3] An important distinction is made in the study regarding the definition of *totally blind*. Note that a small percentage (approximately 2%) of students classified as blind possessed enough residual sight to make use of Large Type, either alone or in combination with Braille writing. For purposes of the study, students with either extremely low acuity or a narrow field of view were classified as *totally blind* [90].

access to a braille printer and no sighted intervention is required for its use. Hence, with the proper processing techniques applied to images, as will be described in the discussion of TACTICS, it may be possible to utilize such a printer to produce adequate tactile representations of pictures.

Vacuum-forming method: This method, also known as "thermoforming," excels at producing multiple copies of a tactile graphic in a very durable format. It requires a raised master made of stable or unpliable material. Next, the master is placed on a perforated tray in the vacuum-forming machine. A sheet of thin plastic is fastened over the master such that it forms an airtight cover. A heating unit is placed over the plastic as air is sucked out from below the master, deforming the now pliant plastic over the master. Once cooled, the plastic sheet is a durable replica of the original. This process can take as little as one minute, which is acceptable for producing multiple copies.

Microcapsule paper: Referred to variously as "capsule paper," "swell paper" or "puff paper," this is a quick and economical way to produce tactile graphics. It is paper that has been coated with microscopic capsules of polystyrene (Figure 1), each being $\approx 100 \mu$m in diameter.

There are two types of microcapsule paper available on the international market. *Flexi-Paper* is a polyethylene-based paper manufactured by Repro-Tronics, in Westwood, New Jersey [64]. It is tan in color and is quite durable under conditions of folding and crumpling. The Matsumoto Kosan Company of Osaka, Japan, produces a paper-based version [51], white in color, that provides for blind persons a more familiar stiff feel resembling that of heavy braille embossing paper while being less resistant to the effects of folding than Flexi-Paper. Both are comparable in price ($\approx$\$1.00 U.S. per sheet). With an unexpanded capsule diameter of 100μm, the unexpanded resolution of both brands is therefore 10^4 *capsules/cm* (2.54×10^4*capsules/in*). The capsules expand upward and outward consistently to a diameter (height) of 0.2mm to 1.0mm, yielding an expanded resolution of 10 to 50 *capsules/cm* (25 to 127 *capsules/in*). In practical observations in the laboratory, the typical expanded diameter is $\approx$0.3mm and typical expanded height is $\approx$1.0mm.

To benefit from this expanded resolution, a printer should have a resolution of at least 127 *dots/inch*, the best possible resolution of expanded capsule paper based on manufacturers' specifications. Thus, a typical laser printer with a resolution of 300 *dots/inch* is entirely adequate for initial output of the image to be expanded. The amplitude of this expansion is affected by the temperature of the heating element, with higher temperatures producing slightly more pronounced expansion.

Original graphics are photocopied onto the capsule paper using a standard office copy machine (Figure 2). Graphics can also be applied to the microcapsule paper using ink pens, markers and other drawing implements. The only requirement is that the graphic be rendered in black. Once the image is applied to the microcapsule paper, it is inserted image side up into a heating machine, referred to as the *Tactile Image Enhancer* (Figure 3). For expanding multiple pages, each exposed sheet of capsule paper must be fed individually into the Enhancer.

When exposed to a heat source of 120-125 degrees Celsius (248-257 degrees Fahrenheit), portions of the paper that are printed in black expand. The microcapsules beneath the black lines of a diagram absorb more heat than the other microcapsules and expand in diameter, raising the drawing from the background (Figure 4).

An added benefit is that one can draw directly on the microcapsule paper, which then can be raised immediately. The time taken to raise one drawing already on a sheet of microcapsule paper is approximately ten seconds. Even accounting for printing from a computer, photocopying onto the microcapsule paper, and subsequent raising, the entire process is still reasonably fast. Instant raised lines can be produced on capsule paper using a new heat-pen device developed by Repro-Tronics.

Other methods: Numerous other methods exist for the production of tactile graphics, although none are widely used. For purposes of completeness we mention only their names here. These additional methods include relief maps, cork maps and graphs, nonfigurative pictures, sewing-machine diagrams, embossed aluminum-foil displays, movable-parts displays, flannel-board diagrams, magnetic-board diagrams, electroforming processing, nyloprint, silk screening, the solid-dot process, foam-ink printing, storm relief printing, and screen drawings. Exhaustive coverage of all of the above techniques are available in a variety of sources, including [11], [19], [20], [78].

These static display methods typically produce long-lasting, effective displays of static visual information. For dynamic information, such as material displayed on a computer screen, other access methods are more appropriate.

B. Auditory Interfaces

This paper focuses on the production of tactile graphic output of information of a primarily graphical or visual nature, but it is worth noting that auditory output is the method of choice for display of textual information for blind computer users [11], [27]. While there is a wide variety of methods for production of tactile graphics, output of computer-generated speech is more generic. Screen review software is used by the blind computer user to explore the textual material and to select the desired passage. Typically, the software sends the text it encounters to a hardware device, such as a speech-synthesis card added as an enhancement to a computer, for conversion from text to speech [76]. One big benefit of speech output is that users who cannot read braille can use it; in addition, it is generally quite affordable. Reliable speech synthesizers are available for most computers, and the quality of speech is typically quite good. Perhaps the most attractive feature of the screen review and speech synthesis output method is adjustable speaking speed, enabling a blind person to listen at 300 *words/minute* or more [11], [71], [78], a speed that is quite competitive with typical sighted-reading speeds of 250 to 500 *words/minute* [18].

The **Nomad** is an example of a multimodal device, combining static tactile graphics with audio output. A tactile graphic, such as a map, is produced and affixed to the display surface of the Nomad. This surface is addressable via computer; and each region can be mapped to sounds that will play in response to the associated region being touched. The Nomad is well suited to museum displays and shopping-mall maps but requires assistance from a sighted person for configuration [19].

Research is underway at the University of Wisconsin exploring the use of an audiotactile snapshot approach [83]. This technique combines computer technology, a touchscreen interface, tactile representations of the computer screen and audio output, to provide multimodal access for blind computer users. It is still in the experimental stage, but some successful tests have been performed with a Windows implementation on a personal computer.

C. Dynamic Tactile Interfaces

Currently, the only dynamic tactile display device in wide use is the **Optacon** (Figure 5a). It is a vibrotactile display, comprised of a fingertip-sized matrix of 144 vibrating pins, arranged in a 24-row, 6-column format. This display is contained in a portable case (8in × 6in × 2in, 4.0 lbs) and is powered by one 5-volt, rechargeable, nickel-cadmium battery. Vibration is caused by piezoelectric film bimorphs, which vibrate with varying amplitude at 230Hz in response to varying levels of current. Its use involves placing the finger of one hand onto the vibrotactile display pad and using the other hand to pass a scanning device over the desired text or image.

The Optacon was designed as an alternative to braille for reading printed text; but reading speeds are slower (50 *words/minute* after months of training and practice) than with braille (104 *words/minute*), and much slower than with synthesized speech output (300+ *words/minute*) [19], [21], [81]. The price of a new Optacon, in the neighborhood of $4,000.00 U.S., is also an issue for some [19], [73]. As of the writing of this paper, the company which produced the Optacon, Telesensory, has discontinued production; and negotiations are underway with another company, Blaise Engineering, to continue production in the future [74].

During use, the pins of the Optacon display react independently in a one-to-one mapping of pixels, or groups of pixels, to pins in response to an image or text passed under the lens of the scanner. Black regions of the scanned item cause pins to vibrate while white regions inhibit vibration. Thus, a letter, line or picture feels like a vibrating replica of the original [73] (Figure 5b). However, the vibrating display produces a noticeable amount of buzzing noise, and the vibration itself tends to temporarily dull the sense of touch on the finger resting on the display after a period of use.

In addition to the Optacon was the **Tactile Vision Substitution System** (*TVSS*), which used a similar technique to display a vibrating representation of an image on a user's back [4], [88]. The image was captured by a television camera and sent to a more widely spaced array of vibrating pins. The idea of the system was eventually to produce a system by which a blind person could wear a video camera and backpack display and actually maneuver through the world using the vibrating representation of what the camera saw for guidance. The technique may have been ahead of its time, being bulky and noisy, even by early 1970s standards. Modern technology may yet produce such a system for independent, walk-around vision replacement [7], [13], [17].

D. Dynamic Tactile Display Research

Enabling blind persons to access visual data on a computer meaningfully is an area of vigorous research. Some of the more pertinent projects from the present and near past include:

- A virtual tactile tablet incorporating a vibrotactile display module demonstrated that increasing a graphic's size and its display resolution improved recognition, while merely varying the geometric complexity of a graphic did not dramatically effect object recognition [89].
- Experiments with a single-pin tactile mouse revealed that immediate tactile feedback improved response times in GUI navigation tasks [75].
- The use of nickel-titanium shape-memory allow (SMA) to provide actuation of a tactile display shows promise as the basis for a lightweight and portable display, although the power consumed and the heat produced by such a display are still high. Further, current shape-memory alloy suffers from brittleness, slow response and recovery times, and lack of long-term durability [28].
- A 64-solenoid, four-level, pin-based fingertip display, used to investigate tactual comprehension improvement through representation of levels of graphics image intensity by varying pin heights on the display [23].
- A virtual tactile computer display which uses electromechanically actuated pins in a rectangular tactile array comparable in size to the sensing area of the fingertip [34].
- The use of polymer gels, or electrorheological fluids, for fabrication of actuators which then conceivably could be used in the development of a tactile display. Such fluids become firm when current is passed through them and could also serve as the basis for a direct-touch, deformable tactile display [22], [56], [57], [60].
- Past research delved into electrocutaneous stimulators, which delivered tiny electrical shocks to the skin, and air jet stimulators, which replaced the pin array with an arrangement of tiny holes where puffs of air are aimed at the skin [17]. Neither of these methods was particularly successful; these two methods are generally accepted by the mainstream research community as unworthy of further consideration.

E. Haptic Interfaces

The term *haptic* refers to the proprioceptive, or positional, sense, which is an extension of touch [35]. Thus, a haptic interface can represent three or more dimensions whereas a tactile display provides only two dimensions. Haptic interfaces are an important display method in virtual reality systems, capable of reproducing a sense of position in space, interaction of forces, and even textures. Of course, the original information must be multidimensional as well, often generated by math-graphing packages or custom graphing software.

Examples of this highly active area of research include development of a method for display of graphs of mathematical functions and scientific data using a three-degree of freedom device called the PHANToM [25], [24], [52], protein molecule docking simulations [10], three dimensional volume haptization [30], and successful experiments in simulating textures with an enhanced joystick device [54], [55].

These devices are generally very expensive ($10,000.00 U.S. and up) and so are still relegated to a small number of research facilities. It is hoped that eventually affordable haptic interfaces will be readily available, providing blind computer users with an even greater ability to explore traditionally visual information physically. An in-depth study of haptic interfaces is beyond the scope of this work, although progress in this area is clearly important to note. An extensive bibliography on this topic is available in [55].

F. *Moving Toward Effective Tactile Display of Graphics*

Audio output is not a solution for most graphics problems because of the difficulty of extracting meaning from a picture, known as the Image Understanding Problem [6], [9], [65], [68]. In order for synthesized speech output to provide adequate and automatic access to an image, the image would first have to be understood by the computer, an unlikely occurrence at present. The most promising direction for research is toward creation of a refreshable tactile display. Such a display would be the tactile equivalent of a standard computer screen, or cathode ray tube, providing direct access to the graphical contents of the computer.

For such a dynamic display to be usable by blind persons, attention must be paid to how graphic material is to be displayed. Clearly, the fingertip possesses a much lower resolution than the eye, so complex visual information must be simplified somehow. Developing a system for performing such simplification, including factors related to method, effectiveness, usability, and future applicability, is the scope and direction of our research.

IV. Manipulation of Images

An *image* is an alternative representation of some visual scene [46], [68]. These representations include sketches, drawings, photographs, computerized graphics and pictures, and motion picture film and videotape. We restrict our discussion to computerized images.

In order to create a computer image from some other type, some form of *quantization* is performed. In this process, samples of the image are taken using a scanner or digital camera at some regular interval and size, based on the desired resolution of the final quantized image. Each sample is assigned a discrete value, or set of values, that represent the intensity or color of the sample as closely as possible [63], [68].

The basic unit of the computerized image is the picture element or *pixel* [46]. For images represented solely as shades of gray, each pixel is assigned a single value, typically an 8-bit integer. Thus, such an 8-bit *grayscale* image has an intensity range of 256 levels of gray, with 0 typically indicating black and 255 indicating white. Similarly, color images typically have three such 8-bit intensity levels associated with each pixel, one each for the *R*ed, *G*reen and *B*lue components[4].

For purposes of this research, we consider primarily complex computer images, quantized representations of photographs, electron micrographs, individual video images, etc., as these present the greatest difficulties when creating a tactile representation. Simple images, such as sketches, diagrams, and line drawings often can be converted straightforwardly into tactile form. Complex images are typically comprised of a broad and unpredictable mixture of shape, color, intensity, and other real-world complexities, presenting the most significant challenges to access by the blind computer user.

Image processing is a broad term describing the algorithmic transformation of an image from one form to another [63]. Processes are divided into general categories of: (1) *point processes*, (2) *area processes*, (3) *frame processes* and (4) *geometric processes* [46].

1. **Point processes** are the simplest and most frequently used of the image processing operations. A point process is an algorithm that modifies a pixel's value in an image based solely upon that single pixel's value or location. Common point processes are image brightening, negative images, image thresholding, image contrast stretching and image pseudocoloring.
2. **Area processes** use groups of pixels surrounding a central pixel of interest to derive information about an image. This group of pixels, often referred to as a *neighborhood*, is examined in some algorithmic fashion as a group. This examination, for instance, can determine the brightness trend information or spatial frequency, with the result utilized in determining a new value applied to the central pixel of the neighborhood. Examples of area processes include edge enhancement and detection, image sharpening, smoothing and blurring, and removal of random noise.
3. **Frame processes** use information from two or more images, or video frames, together with a combination function to produce a new image. Among the many practical applications of frame processes are motion detection, background removal, image-quality enhancement and image combination.
4. **Geometric processes** change the spatial positioning or arrangement of pixels within an image based upon some geometric transformation. Typical operations performed by geometric processes include image scaling, sizing, rotation, translation and mirror imaging. Example uses include

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[4] Although color images are frequently represented in this *RGB* format, numerous other representational schemes exist. Among the most frequently used of these methods are: Cyan, Magenta and Yellow (CMY), Hue, Saturation and Value (HSV), Hue, Saturation and Lightness (HLS), Hue, Saturation and Intensity (HSI), and Hue, Chrominance and Intensity (HCI).

spatial aberration correction, image composition and special effects.

A. Image Processing Algorithms

There are a great many algorithms that process images to produce a wide variety of effects [5], [6], [46], [62], [63], [66], [77]. We are concerned here with the effect more than with the specific means. For a thorough understanding of how the classes of algorithms we have chosen operate on images, and how they relate to our goal of image simplification, we present a brief and somewhat simplified introduction to each of them. For purposes of this discussion, we assume that an image is grayscale, although these algorithms have forms that work equally well for color images. Since we are concerned neither with moving images nor geometric transformations, we do not consider frame or geometric processes; rather, we restrict coverage to a number of point and area processes. Detailed theoretical treatment of image processing techniques is available in [63], while an implementation-oriented approach is given in [46].

For clarity, the notation we use to describe images and image processing algorithms is defined here. A grayscale image X of overall width w and height h can be represented by a two-dimensional array of points, each of which has a certain value, denoted by $X_{m,n}$, representing the brightness or intensity of that point.

A color image has a set of three intensity values, one each for the red, green and blue components of each pixel, associated with each position in the array. Formally, an 8-bit grayscale image is described by:

$$X = 1 \leq m \leq w,\ 1 \leq n \leq h,\ X_{m,n} \in \{0, 1, \ldots, 255\} \tag{1}$$

The set of points N in a square region of width w' surrounding a given point is the *neighborhood* of that point. For points that are closer than $\frac{w'-1}{2}$ points to an image boundary, the neighborhood will include only those points falling within the image. The neighborhood of a point $X_{m,n}$ is denoted by the set:

$$\begin{aligned} N_{m,n} = \quad \{ \quad & w' \text{ is odd}, \\ & \max(m - \tfrac{w'-1}{2}, 1) \leq i \leq \min(m + \tfrac{w'-1}{2}, w), \\ & \max(n - \tfrac{w'-1}{2}, 1) \leq j \leq \min(n + \tfrac{w'-1}{2}, h) : \\ & X_{i,j} \\ \} & \end{aligned} \tag{2}$$

An algorithm a is represented by a mathematical function F_a that transforms an image X into a processed image Y, as follows:

$$Y = F_a(X) \tag{3}$$

The results of our implementations of the following image processing algorithms can be compared with the original image in Figure 6a.

Edge Detection: An edge detection algorithm attempts to locate and highlight *edges* in an image (Figure 6b). These edges are simply the portions of an image where there is a rapid change in intensity. The faster such a transition is made from light to dark, or vice versa, the more likely an edge detection algorithm is to consider the center of such a transition as an edge. Each pixel that is found to be part of an edge is set to the color white, while non-edge pixels can be left alone or assigned the color black using some thresholding function. A common version of this algorithm is the Sobel edge detector, which accomplishes edge detection by using the scaled average of one of a 3 × 3 pixel neighborhood's horizontal or vertical directional derivative, as first described in [62]. The Sobel edge detection function makes use of two matrices, or masks, one each for the vertical and horizontal directions:

$$V = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix} \quad H = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix} \tag{4}$$

These masks are *convolved* over an image. In the case of Sobel edge detection function F_S, the two masks V and H are applied as follows for each point (m, n) in image X:

$$A_{m,n} = N_{m,n} \times V \tag{5}$$

$$B_{m,n} = N_{m,n} \times H \tag{6}$$

$$A'_{m,n} = \sum_{u \in A_{m,n}} u \tag{7}$$

$$B'_{m,n} = \sum_{v \in B_{m,n}} v \tag{8}$$

$$F_S(X_{m,n}) = \sqrt{{A'_{m,n}}^2 + {B'_{m,n}}^2} \tag{9}$$

This is a very computationally expensive operation to perform, particularly for larger images, due to the necessary 20 multiplications, 19 additions and 1 square-root operation per pixel. There are numerous methods described in the literature that can speed up this process.

Blurring: Often referred to in the literature as *low pass filtering*, blurring reduces the detail in an image by removing the high frequency component [68]. It accomplishes this by using the values of all pixels in a neighborhood, assigning some function of those values to the center pixel. Application of either a Gaussian or averaging function are two common techniques to accomplish blurring. Averaging is the most straightforward and fastest technique and, considering the low resolution of the human fingertip, is sufficient. The blurring function F_B is described as:

$$F_B(X_{m,n}) = \frac{\sum_{v \in N_{m,n}} v}{|N_{m,n}|} \tag{10}$$

Applying this function to all pixels in an image produces a blurry version of the original image (Figure 6c). This is also described as the convolution over X by a blurring mask or *kernel*. For example, the blurring algorithm used in this research is accomplished with the following 3 × 3 kernel B:

$$B = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} \tag{11}$$

Segmentation: Images are generally comprised of one or more regions, defined as sections or segments of an image whose members are all closely related by color or intensity. Segments are essentially the areas between edges. A common technique for locating segments is called *K-means segmentation* [45], [66], [79] (Figure 6d). In this algorithm, each pixel is assigned to one of some number K of different groups, or intensity levels, based on its own intensity level. This assignment serves to divide pixels with closely related intensities into like groups or *clusters*, producing an image that is segmented by intensity. A similar segmentation can be performed based on color. Algorithmically, the K-means segmentation applied to image X can be described as follows [79]:

- *Step 1.* Choose K initial cluster centers $z_1(1)$, $z_2(1)$, ..., $z_K(1)$. These can be chosen arbitrarily as, say, the intensity values of the first K pixels in X, or evenly spaced across the range $0 - 255$ as is implemented in our system.
- *Step 2.* At the kth iterative step distribute the intensity values $\{X_{m,n}\}$ among the K cluster domains, using the relation:

$$X_{m,n} \in S_j(k), \text{ if } |\mathrm{X_{m,n}} - \mathrm{z_j(k)}| < |\mathrm{X_{m,n}} - \mathrm{z_i(k)}| \tag{12}$$

$\forall i = 1, 2, \ldots, K, i \neq j$, where $S_j(k)$ denotes the set of intensity values whose cluster center is $z_j(k)$.

- *Step 3.* From the results of *Step 2*, compute the new cluster centers $z_j(k+1), j = 1, 2, \ldots, K$, such that the sum of the squared distances from all points in $S_j(k)$ to the new cluster center is minimized. This is simply the mean of $S_j(k)$, given by:

$$z_j(k+1) = \frac{\sum_{X_{m,n} \in S_j(k)} X_{m,n}}{|S_j(k)|}, j = 1, 2, \ldots, K \tag{13}$$

It is from this manner in which each of the K cluster centers are iteratively updated with the average value for each cluster that the name "K-means" is derived.

- *Step 4.* If $\mathrm{z_j(k+1) = z_j(k)}$ for $\mathrm{j = 1, 2, \ldots, K}$, the algorithm has converged and can be terminated. Otherwise, go back to *Step 2* and continue.

The fundamental drawback of this general statistical analysis of, or *histogram-based* approach to, image segmentation is the inherent disregard for spatial coherence [59]. *Adaptive segmentation* attempts to take into account a smaller portion of an image, producing a segmentation based only on that portion. The effect of this process can be to retain more of the original image information, producing a segmentation which more closely resembles the original (Figure 6e). This result often is achieved at some computational expense and many times produces a result only marginally better than a straightforward segmentation algorithm for purposes of image simplification and automatic tactile graphics generation.

As implemented, the adaptive version of the algorithm performs the same steps as the K-means segmentation algorithm, with the difference being that it operates to convergence on each pixel in X before moving to the next pixel. Thus, the K-means algorithm is performed on some subset or *window* of, and in complete isolation from, the image as a whole. Inspiration for this implementation is drawn from portions of an adaptive segmentation algorithm that uses a Gibbs random field model and a hierarchical approach described in [59].

Negation: The *negation* of an image is produced by inverting the intensity value of each pixel in the image (Figure 6f), assigning this new value to each pixel in turn. Negation is described by this simple function:

$$F_N(X_{m,n}) = 255 - X_{m,n} \tag{14}$$

Negation often is applied in conjunction with another algorithm. In the case of a strictly black and white or *binary* image with more black than white, subtracting the intensity of each pixel from the maximum reverses the field and makes foreground features such as edges black. This negation hopefully improves the legibility of a tactile image, specifically when it is output on microcapsule paper, since the black portion of the image raises while the white portion remains flat.

Median Filtering: Median filtering is a method for removal of *noise* from an image [63]. Generally, *noise* in an image is described as an individual pixel of greatly differing intensity, or *outlier*, compared to the typical pixel in a neighborhood. Differentiating noise from minute detail, or filtering out noise while leaving the desired image intact, is often not so straightforward [2], particularly when an image is complex. Performing edge detection on an image tends to accentuate these outliers, whether noise or detail.

The median filtering algorithm sorts the intensity values of pixels in a neighborhood, assigning the median value of the neighborhood to the center pixel. This is repeated for all pixels in the image, with the effect being a reduction in the number of outliers while preserving edges and non-noisy portions of the image (Figure 7). An especially fast version of the median filtering algorithm can be found in [32]. The function F_M for median filtering can be described as:

$$F_M(X_{m,n}) = \mathrm{Median(N_{m,n})} \tag{15}$$

B. Applicability of Image Processing

Production of tactually perceivable tactile images bears some similarity to the challenges of the field of computer vision. The aim of computer vision is automatically to provide analysis of an image on which some decision can be based [9], [58]. Image processing techniques are invariably used in this task to transform an image in such a way as to produce some form of useful output. Similarly, the aim of TACTICS is to present a visual image in a tactile format such that it is useful in some way to an observer. Image processing techniques would appear to be a natural approach. The limits to tactile resolution, and the understood importance of reducing to an essential minimum the information presented to the fingertip, clearly calls for a simplifying transformation of complex images.

In Part II, we demonstrate the use of these algorithms within the visual to tactile translation task. Algorithms are applied in a sequence to an original computerized image, producing a simplified version. This simpler representation is output and raised using microcapsule paper and the enhancing device, generating a tactile version of the original. We develop and evaluate this process in Part II.

V. SUMMARY

In Part I of this two-part paper we reviewed a variety of issues in the areas of human factors, access technology for tactile graphics production, and image processing. A number of the most pertinent of these parameters are collected in Table III. The background information presented in this part will motivate the development and testing of a prototype visual-to-tactile translation system in Part II. The design of our *TACTile Image Creation System* (TACTICS) draws from this background, applicable image processing techniques, and principles of psychophysics to attempt the unsupervised conversion of pictorial information from visual to tactile form. In Part II, we evaluate the effectiveness of TACTICS at producing tactile output that is discriminable, identifiable and comprehensible. This evaluation is accomplished through a series of experiments, and an analysis and discussion of the results of these experiments together with a number of anecdotal observations. Finally, potential directions for future research in this are proposed.

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TABLE I

Summary of information bandwidth limitations for three senses [39].

Sense Modality	*Limit bits/sec*
Skin (vibrotactile)	10^2
Ear	10^4
Eye	10^6

TABLE II

Reading modes used by a group of 7,987 totally blind students.

Method	*Percentage*[5]
Aural	61
Braille	37
Braille & Large Type	1
Large Type	1

TABLE III

Summary of parameters relevant to TACTICS and tactile image perception.

Factor	*Parameters*
Ratio of tactual to visual bandwidths	1:10000
Minimum discernible separation of two points (static)	≈2.5mm
Minimum discernible displacement of a point on a smooth surface	0.002mm
Height of braille dot	0.2-0.5mm
Minimum discernible separation of groves in grating (dynamic)	1.0mm
Resolution of laser printer	76.2-152.4 dots/mm (300-600 dpi)
Resolution of microcapsule paper (expanded)	1-5 capsules/mm
Expanded displacement of microcapsule paper	0.2-1.0mm
Resolution of human fingertip	≈1 dot/mm
Resolution of fingertip compares with:	very blurry vision
Human memory organization	Hierarchical: general to specific
Congenital blindness	onset up to age 5
Adventitious blindness	onset after age 5
Blind population (worldwide)	30-40 million
Blind population (U.S.)	≈500,000
Braille fluency (U.S. blind population)	<16%
Best size for tactile image	7.62-12.7cm (3-5in) on a side

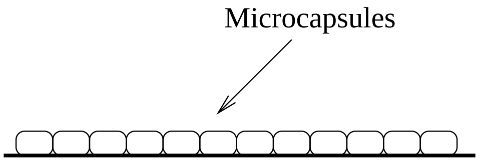

Fig. 1. Microcapsule paper showing layer of polystyrene microcapsules on polyethylene or paper transport medium.

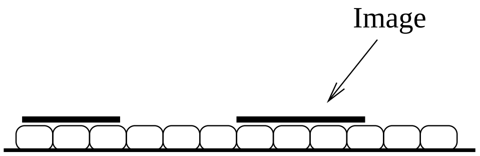

Fig. 2. Microcapsule paper after image is affixed to the surface by photocopying or ink drawing.

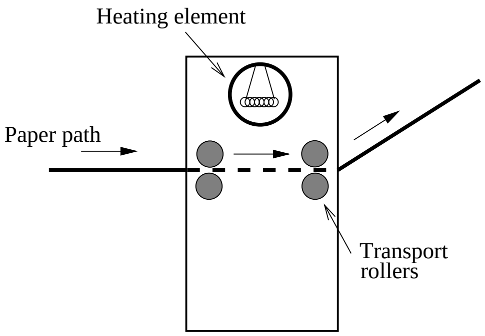

Fig. 3. Simplified view of the Tactile Image Enhancer, showing internal workings of the device for expanding previously exposed capsule paper.

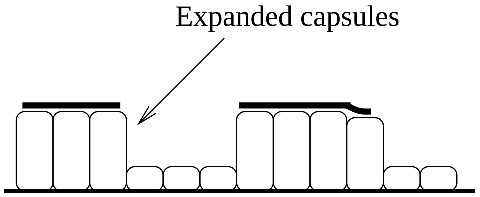

Fig. 4. Microcapsule paper after exposure in image enhancer, showing expanded capsules.

(a) Use of Optacon. User places index finger of one hand on vibrotactile pin array and guides scanner across material to be viewed with other hand.

(b) Active pin matrix display of the Optacon, demonstrating display of the capital letter S.

Fig. 5. Optacon

(a) Unprocessed (b) Sobel edge detection (c) Blurring

(d) K-means (e) Adaptive K-means (f) Negation

Fig. 6. Image processing algorithms

(a) Before (b) After

Fig. 7. Median filtering of a noisy image