

A Color Detection Glove with Haptic Feedback for the Visually Disabled

Helen N. Schwerdt*, Jonathan Tapson⁺, and Ralph Etienne-Cummings*

*Department of Electrical and Computer Engineering, Johns Hopkins University, Baltimore, MD 21218

⁺Department of Electrical Engineering, University of Cape Town, Rondebosch 7700, South Africa

Abstract—The following paper describes the design and preliminary results of a compact color detecting and feedback system. The device is intended for use by those with vision-loss or disabilities who may benefit by a means of perceiving color. The device consists of a glove incorporating optical color sensors along with tactile switches affixed to the fingertips, a haptic feedback interface wrapped around the fore arm, and a microprocessor unit to control communication between sensing and feedback. The color data and finger selection is encoded to spatial and temporal parameters on tactors. The study extends on earlier investigations by Tapson et. al. that have successfully demonstrated the capability of accurately identifying colors through haptic feedback. To further extend the field, the present research attempts to characterize color information in a temporally and spatially continuous representation to more realistically map the features of color space, and allow higher resolution of color perception.

Index Terms—color perception, sensory substitution, tactile displays, haptic user interfaces

I. INTRODUCTION

Many challenges are faced by the disabling effects of blindness. Vision disability includes, but is not limited to, the loss of spatial perception, color perception, and object identification. These disabilities restrict the blind population not only in daily routines but also in employment. According to the NFB (National Federation for the Blind) and the WHO (World Health Organization), it has been reported that only about 30% of blind individuals are effectively employed in the United States, with over 1 million in the United States, and approximately 37 million worldwide possessing the disability [1-3].

Color perception is an often overlooked ability that humans frequently use to gain a large amount of information, spanning a wide range of content. The range and amount of information that color represents or encodes is invaluable in visual communication, to which the blind have no access. For example, contrasting colors may be used to encode text or detect edges of surfaces. Colors may also symbolize inherent meanings. For example, red is a universal indication of warning, coming from natural representations of fire and blood, and is frequently used to alert humans of upcoming danger or warning. Mixtures or combinations of colors are unintentionally used to identify or distinguish objects.

Cognitive studies of color vision and perception frequently demonstrate the intrinsic relationship between color perception and visual objection recognition [15-16]. Whereas, the blind accomplish this same task of object recognition by discerning textures. Thus, while color, in itself, is defined by the spectral wavelength of light, it nevertheless unintentionally or intentionally visually communicates practical information to humans. The skill of color perception, therefore, does not limit itself to learning to identify discrete colors, but rather, how information is perceived by color relations. Just as the blind learn Braille as a means of understanding text, color perception may provide an alternative and more practical means of not only perceiving text, but also, perceiving objects, environments, and possibly even the aesthetic beauty of art. The potential ability of the blind to have a means of acquiring this information by substituting the visual senses with an alternative means of perception may present an invaluable capability.

II. BACKGROUND

A. Existing Devices

To overcome some of the challenges faced by individuals with blindness or other visual impairments, a number of devices have been developed to aid the blind in spatial orientation and object recognition. Existing systems include blind canes that use ultrasound to perceive the proximity of approaching objects or RFID to identify “tagged” objects within the vicinity of the user [4]. More elaborate devices, such as the Fingersight device, incorporates a laser, videocamera, and phototransistor into a sensor for spatial recognition and a cell phone vibrator for haptic feedback to the user [5]. The laser detects abrupt changes in color and depth (edges) of surfaces, and the videocamera further provides identification of other features of the object represented by the sensor using computer algorithms. Along with depth perception, the Electro-Neural Vision System implements a videocamera for color perception as well, and provides electro-tactile feedback by multiple arrays of electrical pulses to the fingers [6]. While the latter two devices have tremendous potential for providing substantial visual information to those with visual disabilities, there has been a concurrent difficulty of approaching the task of communicating the complex and multifaceted forms of visual

information (depth, color, object identification, etc.) in a way that is easily understandable and perceptual.

An alternative measure that has seen increasing advancements in recent years may completely restore vision by surgically implanting electrical chips at the retina [17]. However, not only are these techniques invasive and costly, the procedure is still in infancy stages, and the use of these restored functions on those born blind, rather than those disabled later in life, have shown varied success. Furthermore, the possibility of integrating color perception on these chips is yet to be investigated.

B. Recent Studies in Color Perception

Methods of communicating only color information through sensory substitution have more recently been developed. One approach to perceive color may replace vision by the auditory senses. The “SoundView” system allows users to move a pointer above a colored image display while listening to sounds created based on the color below the pointer and the motion of the pointer [7]. The system creates color-dependant sounds by implementing various filters to encode colors based on their hue, saturation, and brightness (HSB) components. However, the research is relatively undeveloped and human testing is yet to be carried out. Color perception through the sense of touch has more recently shown increasing success. The basis for haptic feedback in sensory substitution mainly deals with its unobtrusive and more user intuitive nature [8].

To provide a straightforward means of color perception as well as an indirect approach to object recognition, a color sensing glove was designed to align with the following goals and objectives; unobtrusive, compact, mobile, and providing a means to learn color. The glove is intended to provide those lacking visual senses with an alternative means of perceiving color at a high temporal and spatial resolution. Currently, the glove uses two color sensors fixed to the fingertips of the thumb and index finger, four corresponding tactors wrapped around the forearm, and a microprocessor unit attached to the surface of the hand, as shown in Figure 1. The study examined the use of multiple color sensors in order to pursue a multi-dimensional conception of color to correlate with the natural setting of color in the environment. However, unlike camera based approaches, attachment of the sensors on the fingers allows for an implicit fusing of “form” and “function”. That is, the user may recognize an object by its shape by feeling it through the user’s fingers (correlating with “form”), and then may recognize the object by its color through the color sensors on the user’s fingers (correlating with “function”). Furthermore, the present work pursued a device that may be easily worn and compact to attain to one of the objectives of creating an unobtrusive mechanism of color perception.

III. HARDWARE

The color glove integrates three functional units: (1) the color sensors, (2) the microprocessor unit, and (3) the tactile display. The entire device requires a single supply of 3.3 volts during normal operation and 5 volts during programming.

Presently, the tactile display is appended to forearm-bands. The forearm-bands allow for varying arm sizes and one may envisage the tactile display directly attached to a longer extending glove in the future to create a more mobile device. Thus, the color glove is capable of battery operation and represents a potentially compact and mobile form. A computer is used to program the microprocessor unit, manipulate gain settings of the color sensors, receive digital recordings from the color sensors, and encode the digital color recordings for corresponding control of the tactile display. A flow diagram illustrating the interaction between these components is shown in Figure 3.

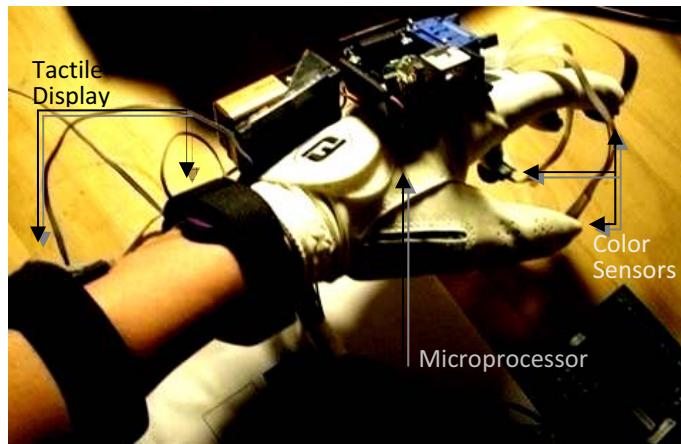


Figure 1. The tactile display (left) is implemented by attaching 2 tactors to the posterior and anterior sides of the forearm on each armband. The microprocessor unit can be seen attached to the top surface of the glove, along with a 9V battery below it. Three color sensors are attached to the fingertips, but only two of these are used.

A. Color Sensors

Two color sensors are attached to the glove; one below the index finger and the other below the thumb finger. Multiple color sensor placements may allow for a more multi-dimensional sensing of color. An optical color sensing IC from Avago Technologies (ADJD-S371-QR999) was soldered onto a small, 1 by 1 cm, PCB, with its corresponding components, to fit below the fingertip. An overlaying PCB was interleaved into the glove finger tips with a membrane-pushbutton switch, such that the user can directly control on-off functions of the sensors. The two PCBs are sandwiched across the glove fabric and connected by wiring together four parallel pin holes through the fabric.

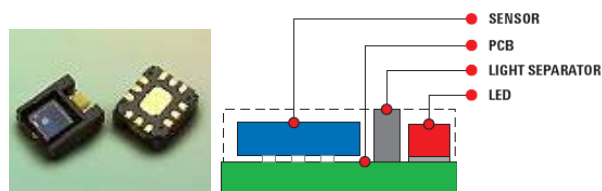


Figure 2. The left picture displays the surface mount Avago ICs, where the sensor element is seen in blue and is divided from the yellow LED. The right illustration identifies the individual elements of the chip.

The Avago chip is available in a surface-mount package with a footprint of only 3.9 mm by 4.5 mm (Figure 2). Color detection is accomplished by utilizing the chip’s integrated

white LED and CMOS IC with Red-Green-Blue (RGB) filters. The LED provides an independent light source to isolate the surface from ambient light and create a more precise environment to measure reflected light. The integrated sensors convert the amount of light reflected from the LED to a 10-bit digital value. This conversion occurs over its red, green, and blue filters, thus measuring the amount of red, green, and blue found on a surface. In this way, the chip serves to measure color by measuring light intensity as a function of the red, green, and blue colors. The gain of the sensor may be configured by manipulating the amount of integrated capacitors and/or integration time used. The chip implements an Inter-Integrated Circuit (I²C) bus to transmit and receive serial data. Thus, communication requires only two bidirectional, open-drain lines; serial-data (SDA) to receive digital color measurements and send gain configuration settings, and serial-clock (SCL) to synchronize transmission. The chip's LED is powered by a constant supply of current provided by the Fairchild IC (FAN5612) to enable a low power and invariable illumination environment for optical readings. In order to more effectively remove ambient light, a black rubber enclosure surrounds the Avago IC, isolating the reflected light from the LED source during color measurements to produce more precise digital readings.

In order to conserve power during idle mode (wearing glove, but not actively pursuing to sense any color), push-button membrane switches (Panasonic – EVQ-Q2H02W) enable the user to initialize color sensing operations as soon as the user's finger tips contact objects with minimal force (100 g-F). The switches control activation of the Fairchild IC in order to power on or off the LEDs, and communicate its current on/off states to the microcontroller at the microprocessor unit. The switches are 6 by 6 mm in surface size and 2.5 mm in vertical height. They are small enough to be placed interior to the glove for direct contact with the user's finger tips. Wiring through the glove material links the sensor PCBs mounted exterior the finger tips.

Each color sensor requires five I/O connections, comprising the serial-data pin (SDA), the serial-clock pin (SCL), switch status, and power (3.3 V supply and ground).

B. Microprocessor Unit

The microprocessor unit is attached to the back of the glove along with a 9V battery. This PCB comprises the microcontroller (Microchip® dsPIC30F4011) and includes control and communication functionality and ports; microcontroller programming modular jack, RS-232 communication and connector for the tactile display and the computer, 15-pin port to link up to 3 color sensors, and 6 possible PWM outputs for alternative feedback mechanisms.

The microcontroller is utilized to communicate with the color sensors, transmit to a computer and the C-2 tactors testing interface, and perform various encoding and translational operations. In order to send and receive data to the color sensors, I2C modules were manually programmed to activate I2C on multiple I/O pins of the microcontroller. Serial

communication to the computer and tactile interface is accomplished by using the onboard UART modules on the microcontroller.

The microprocessor unit can be directly connected to the serial port of a computer to display real time digital RGB readings on Matlab®, configure gain settings on the color sensors, and control PWM timing and duty cycles. The serial port of the microprocessor unit can also be connected to the C-2 testing interface to control the tactors of the tactile display.

C. Tactile Display

Various haptic feedback mechanisms were tested, including cell phone vibrators (Jameco®), micro-piezoelectric TULA-35 actuators (Piezotech®), and C-2 tactors (EAI®). Among these, the tactors were found to be the most efficient and practical.

Four tactors were made available along with a testing interface from Engineering Acoustics, Inc. (EAI). These disk shaped vibrotactile actuators are 3 cm in diameter and 8 mm thick. The tactors implement electromagnetic transducers to create vibrotactile feedback driven by sinusoidal electrical inputs [10-11]. Unlike more commonly used vibrotactile devices which create unreferenced vibrating forces, the tactor incorporates a moving “contactor” to create centered points of tactile sensation [12]. The precise localization of force was imperative in order for users to accurately resolve tactile sensations presented near one another. Each tactile pulse was fixed as a 30 ms duration of vibrotactile stimulus at a pre-established resonant frequency of 250 Hz [11].

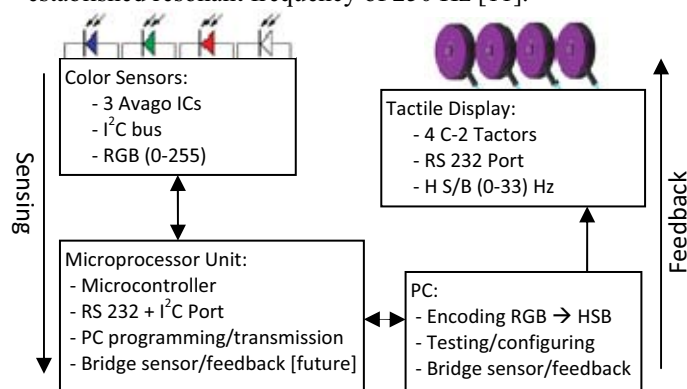


Figure 3. The diagram above highlights the main functional elements and central operations of each unit.

IV. REPRESENTATION OF COLOR

The 10-bit RGB measurements returned from the color sensors are further “encoded” or translated into more perceptible elements of understanding color through a substituted sense mechanism. In earlier studies, tactile feedback applied the trichromatic theory of color by attributing each tactor to each RGB component of these measurements. Thus, each color sensor could channel its measurements directly to three corresponding tactors. Each tactor encodes this information by altering a single point of stimulus such as pulse frequency variation or level of displacement. However, this mechanism entailed significant cognitive loading as users

struggled to correlate a combination of three spatially distinct tactile signals with individual colors. Even discrete red, green, and blue surfaces were arduously identified, since although these colors would activate only a single tactor, depending on the placement on the body and the type of individual stimulus, the two-point linens, or ability of skin receptors to distinguish two spatially separate points of touch, restricts precise signal discernment [13]. Research of color perception methods is fairly limited in terms of substituting the sense of vision with an alternative channel of feedback. However, one study consulted directly with the blind community in order to understand the immediate necessities and aims such devices should exploit in order to be practically useful [8]. The investigation aligned the device's basic objectives to encompass the following properties; unobtrusive feedback, a relational color mapping scheme that enables learning of the color space (rather than identifying discrete colors), and a small learning curve by working with the perceptual space of colors rather than additive or subtractive schemes (such as RGB). The study concluded that haptic feedback was the most unobtrusive method of sense-substituting feedback, and has also been a persistent preference in a number of similar investigations [4-5, 8-9, 11-12], including those that studied audio feedback [7]. To avoid additive or subtractive systems of representing color, a more practical encoding scheme was developed by mapping each color to only two components and using a more perceptual translation of the color space. This was accomplished by mapping RGB to HSB (Hue, Saturation, and Brightness) components, where only Hue and Saturation or Hue and Brightness are used. In this way, the user can directly grasp the concept of the color wheel or the spectral field of color wavelengths, defined by the hue component of color, enabling a more perceptual feel for the relational field of color. The hue component provides users with the primary understanding of color, since it computes the discrete color of a surface, independent of its mixture with other wavelengths of color (Saturation), or its lightness or diffusion with white (Brightness). Thus, discrete colors are represented in a more computationally simple form, since the user essentially requires knowledge of only the hue component, rather than all three R, G, and B components. The Saturation or Brightness component offers the user with additional information regarding the surface color. However, this encoding scheme restricts the user from comprehending the entire (since one component is missing) and realistic setting of color, in its natural form, where colors are frequently mixed and diffused rather than existing in discrete forms. Nevertheless, the process of mapping color from vision to another dimension of sense (in this case, to touch) inherently exposes itself to differences that can only be enhanced by furthering research and functionality in the area of tactile feedback representations of color.

V. METHOD OF ENCODING COLOR

In order to communicate information by the sense of touch, "Tactons", or structured, tactile messages [11], are used to encode the 10-bit color information received from the color sensors. This data is encoded as a means of tactile feedback by

utilizing parameters available on the C-2 tactors. These parameters include spatial location (relative placement and location of the tactors), intensity (amplitude and displacement of the tactors' point of stimulation or "contactor"), and frequency (cycle time of sequencing contactor displacements). Because of the forearm's limited bandwidth in terms of resolving minimal displacements of the tactors' contactor, the intensity parameter is not used. Unlike earlier studies that attempt to encode discrete colors to a limited range of prearranged tactile messages [9], the current study evaluates encoding schemes that allow users to experience the more continuous space of color (ability to relate and distinguish similar colors) as well as process color in real-time/space (ability to discriminate and compare colors in a spatial arrangement and continual feedback as user moves the point of observation; pointer, or the fingertip in this case). Furthermore, this type of encoding system evades the need to memorize tactile messages, but rather creates a more intuitive setting to learn the concept of color, which, as previously discussed, is one of the device's primary objectives.

A. Tactile Parameters

Frequency is used to encode intensity of the color component. However, temporal processing of stimuli differs widely depending on spatial location and frequency. Furthermore, depending on the frequency of stimuli, one must consider differing types of skin receptors; those that handle static tactile stimuli or vibrotactile stimuli [14]. The present study attempts to integrate only stimuli within the range of 0 to 33 Hz such that vibration is considered a minimal source of stimulation since the receptors that process vibratory stimuli require a larger separation for two-point linens.

Spatial location is used to encode the type of color component represented. Spatial location is also used to identify the finger from which color should be encoded. That is, each color sensor corresponds to a pair of tactors that maps its hue and saturation or brightness component. Because the entire device should be limited to the hand portion of the body to represent a compact and mobile form, the tactors were attached to the upper portion of the forearm. Although the fingertips seem to present the ideal site for tactile communication as they contain the most sensitive receptors for spatial acuity [14], feedback in this area may interfere with the sensors already assigned here. The posterior portion of the hand was also abandoned as this area was already designated to situate the microprocessor unit of the device. Elastic bands wrap and bind the tactors around the area just below the wrist. Two tactors are attached to each band, employing both sides of the arm. In order to minimize spatial noise from concurrent activating tactors, the fields of stimuli are isolated by placing a single tactor on each side of the arm.

B. Color and Tactile Information Processing

In order to control and test tactile feedback methods, the tactors connected to EAI's testing interface were functionalized through serial ASCII communication in

software. Because of the limited capacity of skin receptors to resolve differences in minute frequency changes, the color measurements were further compressed to an 8 bit value, and the amplitude of each component (H and S, or H and B) was directly mapped to the frequency of pulsing contactor displacements. Thus, color values of 0-128 were mapped to frequency values of 0-33 Hz per factor (30-500 ms temporal spacing of pulse stimuli, as described in section IIIb). The encoding computation and process was performed in Matlab where measurements returned from the color sensor were evaluated and mapped to corresponding values to control the frequency of the 4 tactors' vibrotactile pulses. Since the testing interface did not allow simultaneous control of all 4 tactors, each tactor independently transmits a sequence of pulses within a 1 second period in succession of each other, a cycle encompassing 4 different sequences to the 4 different tactors.

I²C transmission and reception between color sensors and the microprocessor unit is performed in a cyclic fashion along with the formerly described feedback and encoding operations. Each cycle of tasks is displayed in the flowchart in Figure 4. Each cycle takes about 4 seconds, accumulating the individual periods of tactor sequences and encoding process.

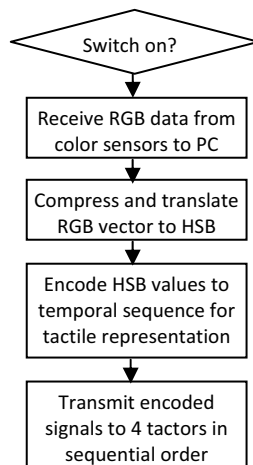


Figure 4. The flowchart outlines the color detection and feedback procedure.

VI. RESULTS

In order to evaluate functionality of the device, measurements returned from the color sensors (compressed to 8-bit) were compared to the actual colors being detected. These results are tabulated in Figure 5. Noise is represented in the data by comparing the actual and detected RGB values, where the values that should ideally correspond to zero instead are offset by a number (approximately 40 for black). This represents shortcomings in the ambient light filter, which had been implemented by surrounding the sensor with a black enclosure.

Tactor functionality was evaluated by ensuring that the frequency range between 0 to 33 Hz was entirely represented and that values encoded from color were accurately transformed to its corresponding frequency as computed in software. These tests demonstrated consistency of the tactor

frequency outputs to computed values. The mapping of HSB to corresponding frequencies transmitted from the H and S tactors or the H and B tactors is illustrated in Figure 6.

	Actual			Detected		
	r	g	b	r	g	b
red	255	0	0	255	147	82
green	0	255	0	104	165	120
blue	0	0	255	77	109	169
yellow	255	255	0	255	255	123
cyan	0	255	255	134	220	255
.5 red	128	0	0	108	68	46
.5 green	0	128	0	79	123	79
.5 blue	0	0	128	47	59	73
white	255	255	255	255	255	255
black	0	0	0	38	43	34

Figure 5. The table displays actual RGB values of various colors being detected to corresponding measured color sensor values.

	HSB Color			Tactor Freq. (Hz)		
	h	s	b	h	s	b
red	0	1	1	33	1.44	0
green	120	1	1	3.7	1.44	0
blue	240	1	1	2	1.44	0
yellow	60	1	1	6.7	1.44	0
cyan	180	1	1	2.6	1.43	0
.5 red	0	1	0.5	33	1.42	0
.5 green	120	1	0.5	3.7	1.42	0
.5 blue	240	1	0.5	2	1.42	0
white	0	0	1	33	33	0
black	0	0	0	33	33	33

Figure 6. The table shows the mapping of colors in HSB form to corresponding tactor frequencies.

VII. DISCUSSION

Testing returned valuable outcomes confirming the device's potential benefits, as well as capacity for improvement. The glove's ability to detect color with high resolution (8-bit) and near real-time (1 second cycles) acquisition signifies the attainment of one of the objectives earlier defined at the end of section II; the potential for users to learn the concept of color space and perceive relations in the field of color rather than identifying discrete colors, as was accomplished in an earlier study [9]. Furthermore, the device's goal of being unobtrusive was successfully demonstrated by restricting placement of its functional components to the area of the hand and upper forearm, and activating tactile feedback only during command of a switch embedded on the fingertip.

On the other hand, testing also revealed several limitations and areas of improvement, which may be resolved prior to human testing. Currently tactile feedback entails sequential activation of four tactors, causing a significant latency in temporal resolution. On the other hand, bypassing the C-2 testing interface to directly link the tactors to the microprocessor unit may allow for simultaneous feedback from all 4 tactors, which would reduce the detection time to a single cycle. Following formal human testing and survey, the device may be further compacted by disconnecting and bypassing the interface for computer and C-2 testing and

allowing the microcontroller to independently accomplish the equivalent tasks. The encoding system may be further improved to filter out noise from ambient light or inherent sensor defects. Additionally, investigation of an alternative scheme of representing colors in the tactile frequency mapping may be necessary, to more equally distribute the range of frequency and therefore allow users to better resolve differences in similar colors.

However, since testing was restricted to the lab-setting, these results do not necessarily imply an equivalent functionality for user operation. Experiments involved the use of a computer as a bridge linking the networks of sense and feedback. Nevertheless, the computer had an important role in allowing extensive experimentation of the individual device components in order to gain insight of their independent limitations and capabilities. The next step would entail formal human testing in order to validate the glove's usability for potential candidates of use.

ACKNOWLEDGMENT

The author would like to thank the members of the Computational Sensory-Motor Systems Lab at Johns Hopkins University for their support, as well as its director, Dr. Ralph Etienne-Cummings. This work could not have been accomplished without the assistance and support from Philippe Pouliquen for building the first version of the color sensing glove interface as well as providing assistance on creating the present device, Bruce Mortimer of Engineering Acoustics, Inc. for providing the C-2 tactor equipment, and the Telluride Workshop on Neuromorphic Cognition Engineering where the first version of this device was tested.

REFERENCES

- [1] National Federation of the Blind. (2008 May) Blindness Statistics. [Online]. Available: http://www.nfb.org/nfb/blindness_statistics.asp
- [2] J. Frank, "Web Accessibility for the Blind: Corporate Social Responsibility or Litigation Avoidance?" in *Proc. 41st IEEE Int. Conf. System Sciences*, Hawaii, 2008, pp. 1- 8.
- [3] T. Pun, P. Roth, G. Bologna, K. Moustakas, and D. Tzovaras, "Review: Image and Video Processing for Visually Handicapped People," *EURASIP J. Image and Video Processing*, vol. 2007, pp. 1-12, Dec. 2007.
- [4] J. Hiebert, F. Jessani, W. Nyman, and K. Schmitter, "Intelligent Cane," in *Proc. ENGG 3100*, Univ. of Guelph, 2007, pp. 35-37.
- [5] G. Stetten, R. Klatzky, B. Nichol, J. Galeotti, K. Rockot, D. Weiser, H. Sendgikoski, and S. Horvath, "Fingersight: Fingertip Visual Haptic Sensing and Control," in *IEEE Haptic, Audio and Visual Environments and Games Int. Workshop*, Pittsburgh, Oct. 2007, pp. 80-83.
- [6] S. Meers, and K. Ward, "A Vision System for Providing the Blind with 3D Colour Perception of the Environment," School of IT and Computer Science, University of Wollongong, Australia, 2000.
- [7] K. Doel, "SoundView: Sensing Color Images by Kinesthetic Audio," in *Proc. Int. Conf. Auditory Display*, Boston, July 2003, pp. 303-306.
- [8] K. Kahol, J. French, L. Bratton, and S. Panchanathan, "Learning and perceiving colors haptically," in *Proc. 8th Int. ACM SIGACCESS Conf. on Computers and Accessibility*, 2006, pp. 173-180.
- [9] J. Tapson, J. Diaz, D. Sander, N. Gurari, E. Chicca, P. Pouliquen, and R. Etienne-Cummings, "The Feeling of Color: A Haptic Device for the Visually Disabled," in *IEEE Biomedical Circuits and Systems Conf.*, Baltimore, Nov. 2008.
- [10] R. Cholewiak, and C. McGrath, "Vibrotactile Targeting in Multimodal Systems: Accuracy and Interaction," in *Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, Alexandria, VA, May 2006, pp. 413-420.
- [11] L. Brown, S. Brewster, and H. Purchase, "Multidimensional Tactons for Non-Visual Information Presentation in Mobile Devices," in *MobileHCI'06*, University of Glasgow, Helsinki, Finland, Sept. 2006, pp. 231-238.
- [12] E. Patieski, and L. Jones, "Vibrotactile Pattern Recognition on the Arm and Torso," in *IEEE Proc. First Joint Eurohaptics Conf. and Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems*, 2005.
- [13] R. Cholewiak, and A. Collins, "Vibrotactile Localization on the Arm: Effects of Place, Space, and Age," *Perception and Psychophysics*, vol. 65, no. 7, pp. 1058-1077, 2003.
- [14] R. Cholewiak, A. Collins, and C. Brill, "Spatial Factors in Vibrotactile Perception," (Cutaneous Communication Lab at Princeton Univ., and Tactile Research Lab at the Naval Aerospace Medical Research Lab), estimated 2000.
- [15] G. Miceli, E. Fouch, R. Capasso, J. Shelton, F. Tomaiuolo, and A. Caramazza, "The Dissociation of Color from Form and Function Knowledge," *Nature Neuroscience*, vol. 4, no. 6, pp. 662-667, 2001.
- [16] P. Skorwski, and L. Chittka, "Towards a Cognitive Definition of Colour Vision," *Nature Precedings*, pp. 1-11, 2008.
- [17] I. Wickelgren, "A Vision for the Blind," *Science*, vol. 312, pp. 1124-1126, May 2006.