BLIND AND VISUALLY IMPAIRED, ASSISTIVE TECHNOLOGY FOR

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INTRODUCTION

Severe visual impairment represents one of the most serious sensory deficits that a human being can have. When this sensory input channel is so impaired that little useful information can pass through it, assistive devices that utilize alternative sensory input channels are often necessary. Familiar examples include the use of Braille and the white cane, respectively, for reading and obstacle avoidance by persons who are blind. Both of these assistive devices provide environmental information to the user via the sense of touch. Other assistive devices provide environmental feedback via the sense of hearing.

In the material that follows, examples of available assistive technology and promising new assistive technology under development for persons who are blind or severely visually impaired are presented. This article begins with an overview of the prevalence and impairments associated with blindness impairments and follows with an examination of reading aids, independent living aids, and mobility aids. The article concludes with a brief look at kinds of assistive technology likely to be available in the near future for persons with severe visual impairments.

The term blindness has many connotations and is difficult to define precisely. To many people, blindness refers to the complete loss of vision with no perception of light. The U.S. government, however, defines blindness as the best corrected visual acuity of 20/200 or worse in the better seeing eye. The acuity designation 20/200 means that a vision impaired person is able to see at a distance of 20 ft (6.09 m) what a person with normal visual acuity is able see at 200 ft (60.96 m). Low vision is defined as the

Encyclopedia of Medical Devices and Instrumentation, Second Edition, edited by John G. Webster

Table 1. Prevalence of Blindness and Low Vision Among Adults 40 Years and Older in the United States[a]

	Blindness		Low Vision		All Vision Impaired	
Age, Years	Persons	%	Persons	%	Persons	%
40–49	51,000	0.1	80,000	0.2	131,000	0.3
50–59	45,000	0.1	102,000	0.3	147,000	0.4
60–69	59,000	0.3	176,000	0.9	235,000	1.2
70–79	134,000	0.8	471,000	3.0	605,000	3.8
>80	648,000	7.0	1,532,000	16.7	2,180,000	23.7
Total	*937,000*	*0.8*	*2,361,000*	*2.0*	*3,298,000*	*2.7*

[a]Abstracted from Ref. 3 Arch. Ophthalmol. Vol. 122, April 2004.

best corrected visual acuity that is worse than 20/40 in the better seeing eye. People with extreme tunnel vision (a visual field that subtends an angle $>20^\circ$ regardless of the acuity within that visual angle) also are classified as being legally blind and thus qualify for certain disability benefits.

It is important to realize that a great majority ($\sim$70–80%) of people with severe impairments has some degree of usable vision (1,2). The severity of vision loss can vary widely and result in equally varying degrees of functional impairment. Although the degree of impairment may differ from one person to another, people who are blind or have low vision experience the common frustration of not being to see well enough to perform common everyday tasks.

The prevalence of blindness and low vision among adults 40 years and older is given in Table 1. According to the National Eye Institute (2), a component of the National Institutes of Health in the United States Department of Health and Human Services, the leading causes of vision impairment and blindness are primarily age-related eye diseases. These include age-related macular degeneration, cataract, diabetic retinopathy, and glaucoma. The 2000 census data revealed >5 million people of all ages in America have visual impairments severe enough to significantly interfere with their daily activities.

CONSEQUENCES OF SEVERE VISUAL IMPAIRMENTS

The two major difficulties faced by persons who are blind or severely visually impaired are access to reading material and independent travel or mobility. Simple-to-sophisticated technology has been used in a variety of assistive devices to help overcome these problems. The term reading is used in this context to include access to all material printed on paper or electronically. Reading material can include text, pictures, drawing, tables, maps, food labels, signs, mathematical equations, and graphical symbols. Safe and independent mobility is used to encompass both obstacle avoidance and navigation. For safe and independent mobility, the first concern is avoiding obstacles, such as curbs, chairs, low hanging branches, and platform drop-offs. After the sight impaired traveler has gained an awareness of the basic spatial relationships between objects within the travel environment, their needs wayfinding or navigational assistance, which involves knowing one's position, one's heading with respect to the intended destination, and a suitable path to reach it.

LOW VISION READING AIDS

People with low vision significantly out number those who are totally without sight (Table 1). Hence, the consumer market for low vision aids is much larger than the one dedicated to people with zero vision. The technology used in low vision aids is rather straightforward and the technologically used is relatively mature. Hence, only a brief overview of such assistive devices will be presented before discussing the more challenging issues faced by persons with zero useful vision. For readers desiring detailed product information about low vision aids, a search of the Internet using the term low vision aids will yield a bounty of pictures, product specifications, and purchasing information.

All low vision aids aim to maximize an individual's residual vision to its fullest. Low vision aids can be categorized as optical, nonoptical, and electronic. Optical aids include handheld magnifying glasses, telescopes mounted on eyeglass frames, and even microscope lenses. Nonoptical aids include enlarged high contrast print and high intensity lamps.

Electronic low vision aids represent the highest level in terms of cost, complexity, and performance. They include electronic video magnifiers that project printed material on a closed circuit monitor, regular television, or computer screen. Electronic video magnifiers can maximize readability of the written material by providing a wide range of magnification, brightness, contrast, type of fonts, and foreground and background colors. A good example of a modern closed circuit TV type of electronic low vision aid is the Optelec Traveller (Fig. 1). This portable video

Figure 1. This portable video magnifier has a built-in 6 in. (15.24 cm) color screen and can magnify text and pictures up to 16 times. (Courtesy of Optelec International, New York.)

Figure 2. Closed-circuit television with computer based text-to-speech output, a talking computer.

magnifier has a built-in 6 in. (15.24 cm) color screen and can magnify text and pictures up to 16 times and more if its video signal is sent to a television set.

People with tunnel vision or central blind spots due to macular degeneration often find it difficult and tiring to read an entire computer screen. For such individuals, the advent of the talking computer (Fig. 2) represented a major technological breakthrough. The capability and flexibility of such a computer or reading machine addressed many of their needs as well as the needs of persons without any useful vision.

READINGS AIDS FOR THE BLIND

For persons with essentially zero useful vision, the tactile sense has been utilized as an alternative sensory input channel for reading. One of the oldest reading substitutes for the blind is Braille, a six dot matrix code that Louise Braille adapted in 1824 for use by blind persons to read written text. The standard Braille cell consists of two columns and three rows of dots separated by 2.3 mm with 4.1 mm separating adjacent cells. Each Braille cell occupies a rectangular area of 4.3×8.6 mm and can represent 2^6-1 (or 63) possible symbols within that areas. Grade I Braille maps each cell a one-to-one basis to each letter of the alphabet, basic punctuation marks, and simple abbreviations so that Grade I Braille has an informational density of approximately 1 bit per 6 mm^2 of surface area. For greater informational compactness and faster reading rates, Grade II Braille uses combinations of dots to represent contractions, frequently used words, prefixes, and suffices. Grade III Braille is even more compact and affords the highest reading rates, but very few people ever master it. The largest proportion of Braille literature is produced at the Grade II level, which can be read at up to 200 words per minute (4) by those proficient in Braille. Braille is a unique reading aid that not only gives blind persons access to printed material but also provides them with a writing medium.

Despite Braille's unique place as a complete writing system that is spatially distributed and retains many advantages of a printed page, Braille is a specialized code that only a small percentage of blind individuals learn to use. This is especially true for persons who become blind after the age of 15 years. Given the difficulty of mastering Braille, the lack of up-to-date Braille printed material, and advances in alternate technologies such as electronic reading machines, many blind individuals choose to not bother with Braille.

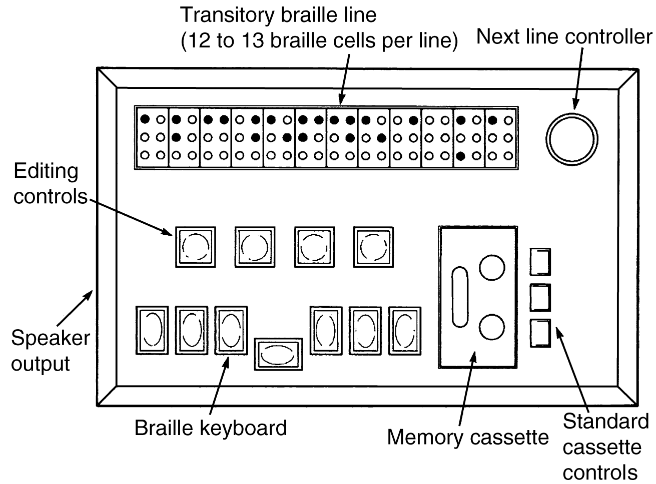

Figure 3. Portable refreshable Braille reader that can playback or store messages using a cassette recorder. The reader has a single-line tactile display, a Braille keyboard, and a tape cassette for data storage and recall. (Picture taken from Fig. 2.8 of Ref. 5.)

Other disadvantages of Braille printed material include the cost to produce it, store it, and maintain it. Embossable Braille paper is not only bulky, heavy, and expensive, the pattern of raised dots (laboriously and noisily impressed into the paper) is fragile and short lived. Assistive technologies such as portable Braille readers (Fig. 3) have mitigated some of the inconveniences associated with Braille (5), but these electronic Braille readers–recorders often do not display the two-dimensional (2D) information embedded in graphs, tables, and mathematical formulas. The single and dual line tactile displays found in most portable readers also makes the rapid search for content via headings very difficult.

Refreshable Braille readers can be used as a computer interface for accessing information on the computer screen. Some full-sized electronic Braille displays are 80 cells long and cost upward of $10,000. The dots in these transient Braille displays are produced by pins raised and lowered (refreshed) to form Braille characters. Refreshable Braille readers allow users to access any portion of the screen information via specialized control buttons and status Braille cells. Tactually distinguishable arrow keys offer screen cursor control while extra status cells provide additional information about text-attributes or line and colon positions.

Refreshable Braille displays are especially useful for deaf blind individuals and users working with computer programming languages. For example, the Braille Voyager 44 (Fig. 4), made by F.J. Tieman BV, has a 44 cell Braille display, and 5 thumb keys for screen navigation. Using its built-in macro program, USB connection, and any screen reader, the Voyager enables a user to access many features of the Windows operating system.

Figure 4. The Braille Voyager 44 made by Manufacturer: F.J. Tieman BV. It has a 44 cell Braille display and 5 navigation keys.

Despite Braille's many drawbacks and limited popularity, its long history, status as the only complete writing and reading system for the blind, and tenacity of advocates like the American Federation for the Blind combine to keep Braille viable as an informational medium. Nonprofit groups like the Braille Institute produce millions of pages of Braille each year for business, schools, government agencies and individuals across the nation. They sell recreational reading material in Braille to both children and adults and provide low cost transcription, embossing, and tactile graphic services.

For the majority of blind persons who do not know Braille, reading material converted into the audio format (aka talking books) and played back on variable speed tape recorders have proven to be popular and convenient to use. To overcome spoken speech's inherently slower reading rate, variable speed tape recorders with special electronic circuits that compensate for the pitch change during high speed playback (1.5–3 times normal speed) can be used. Obtaining reading material in audio form for playback on such recorders also has become more convenient as vendors make downloading of electronic text and audio files available to their subscribers (6).

Although audio books are popular for persons with severe visual impairments, this approach does not work for reading the newspaper, daily mail, memoranda, cookbooks, technical reports, handwritten notes, and common everyday correspondence, such as utility bills and bank statements. Before the advent of a reading machine, which has now become part of a general purpose talking computer, persons with no useful vision relied on human readers with its attendant inconvenience, loss of independence, and lack of privacy.

For severely sight impaired individuals and even those who know Braille, the power, convenience, and versatility of a reading machine, also known as a talking computer, have made it the preferred method of accessing most reading material. First marketed in the early 1980s, reading machines of today are affordable, compact, and can reliably and rapidly convert alphanumeric text into synthetic speech. In addition to a synthetic voice that reads aloud the actual text, the talking computer or reading machine also provides auditory feedback of cursor location and navigational commands.

A talking computer or dedicated reading machine contains artificial intelligence that converts alphanumeric text into spoken speech. The multistep process begins with an optical device that scans the text of a printed document or web page and, using optical character recognition, converts that alphanumeric text string into prefixes, suffixes, and root words (Fig. 5).

The process through which the text string is converted into speech output is somewhat complex and undergoing refinement. The clarity and naturalness of the voice output depend on the text-to-speech technique employed. In general, clearer and more natural costlier sounding speech requires more memory and greater processing power and is thus more expensive.

After the written material has been converted into a text string by optical character recognition software, one of

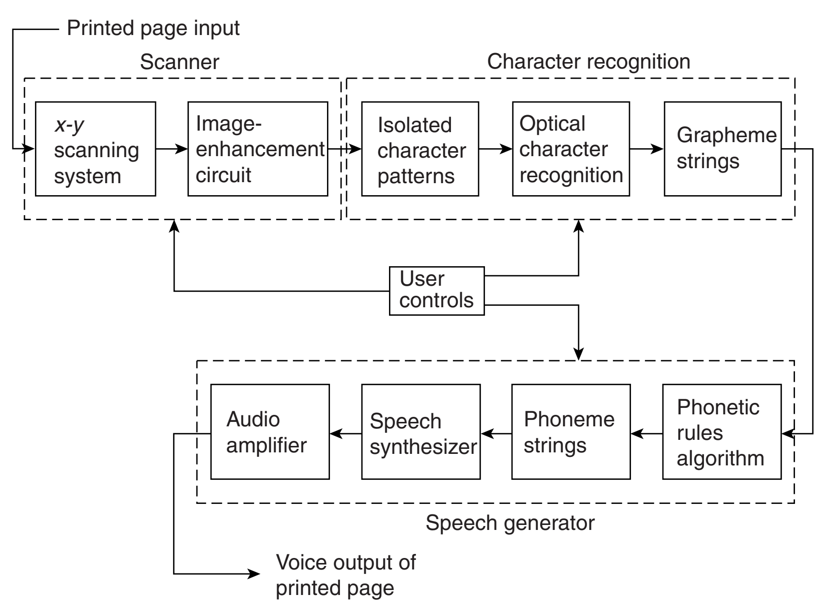

Figure 5. Functional components of a reading machine. (Taken from Fig. 2.18 of Ref. 5.)

three basic methods can be employed to convert the string into speech sounds. The first method is called whole word look-up. It produces the most intelligible, life-like speech, but it is the most memory intensive even for modest sized vocabularies. Despite steady advances in low cost, high density memory chips, whole-word-look-up tends to be prohibitively expensive or the vocabulary is limited (7).

A less memory intensive approach is the letter-to-sound conversion in which a synthetic sound processor divides the text string into basic letter groups and then follows certain pronunciation rules for the creation of speech. Many languages (especially American English) are replete with numerous exceptions to the usual rules of pronunciation. Hence, the quality of the speech output using letter-to-sound conversion depends on the sophistication of the rules and the number of exceptions employed (7,8).

The third method of converting text into speech is called morphonemic text-to-speech conversion. This approach relies on prestored combination of morphemes (basic units of language such as prefixes, suffixes, and roots) and their corresponding speech sounds. Some 8000 morphemes can generate $\sim 95\%$ of the English words (8,9) so this approach avoids the memory demands of the whole word look-up approach. Morphonemic based speech generation generally yields synthetic speech output that is more intelligible than the letter to speech approach, but is more demanding computationally. Continuing advances in technology have now made single chip text to speech converters powerful, capable, and affordable in consumer electronics (10).

A blind individual using a computer running a text-to-speech program can now hear what is on the screen and use cursor keys to select a specific part of the screen to read. Equipped with such a computer, high speed connection to the Internet, and a modern reading machine, sight impaired individuals now have wide access to news, e-mail, voice messaging, and Internet's vast repository of information. These powerful information technologies have reduced the social isolation formerly felt by blind persons while also broadening their employment opportunities.

One example of how recent technological advances are improving access to reading materials is the Spoken Interface that Apple Computer unveiled at the 2005 Annual Technology & Persons with Disabilities Conference held in Los Angeles. Because Spoken Interface is a screen reader that is fully integrated into Apple's operating system, assistive technology developers should be able to set up easy inter-operability between their software and the operating platform with little additional modifications.

Another example of a low cost, user friendly, and powerful text-to-speech software is the TextAloud MP3 by Nextup Technologies (http://www.nextuptech.com/about.html). This software converts any text into natural sounding speech or into MP3 files for downloading and later playback on portable electronic devices (e.g., MP3 players, pocket PCs, and portable data assistants).

MANDATED WEB ACCESSIBILITY

With so much information available on the Internet and the blind people's increasing dependence on it, the United States government included web accessibility in its 1998 amendment of the Rehabilitation Act (11). Section 508 of this law requires that when Federal agencies develop, procure, maintain, or use electronic information technology, they must ensure that this technology offers comparable access to Federal employees who have disabilities. Although the scope of Section 508 is limited to the Federal sector, these requirements have gradually spread to the private sector, especially to large corporations that deal frequently with the Federal government.

The accessibility requirements of Section 508 are reflected in several guidelines, including as the Web Content Accessibility Guidelines (WCAG) from the World Wide Web Consortium (W3C). The WCAG recommendations, which are updated periodically, include implementing standardized style sheets instead of custom HTML tags and offering closed-captioning and transcripts of multimedia presentations. Other recommendations for making a web site compliant (12) include the following: provide text alternates to images; make meaning independent of color; identify language changes; make pages style sheet independent; update equivalents for dynamic content; include redundant text links for server-side image maps; use client-side image maps when possible; put row and column headers in data tables; associate all data cells with header cells; title all frames; make the site script independent.

An assortment of adaptive hardware and software can be effectively utilized once a web site satisfies the WCAG recommendations (13). Persons with low vision can change their browser settings or use screen magnifiers. Internet users who are blind or have very limited vision can use text-based Web browsers with voice-synthesized screen readers, audio browsers, or refreshable Braille displays to read and interact with the Web.

Recent efforts to increase internet's compatibility with assistive technologies used by sight impaired persons include the development and implementation of search engines that read aloud their results using male and female voices. Some websites offer speech-synthesized renditions of articles from news organizations like BBC, Reuters, and the New York Times (14).

While internet accessibility by persons with severe visual impairments is improving, a number of problems and challenges remain. Screen readers or Braille keyboards that blind people use to navigate the Internet cannot scan or render graphical elements into a readable format. Spam, security checks, popup ads, and other things that slow down a sighted person's Web searches are even worse impediments for those with severe visual impairments using assistive technology.

INDEPENDENT LIVING AIDS

Because blindness and severe visual impairments are so pervasive in their impact, numerous and relatively low cost assistive devices have been developed to make non-reading activities of daily living (ADL) easier. In general, these ADL devices rely on the users' auditory or tactile sense for their operation.

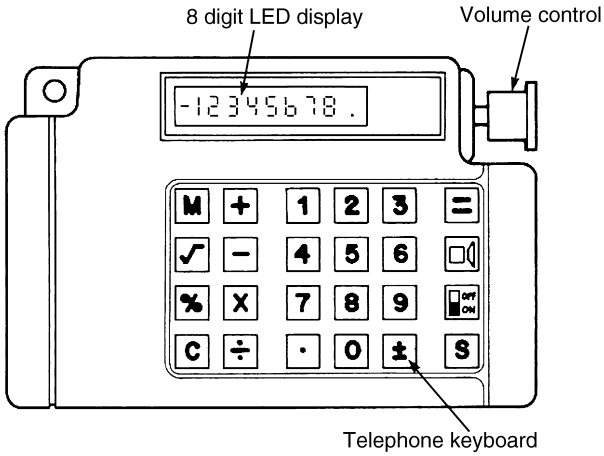

Figure 6. A talking calculator with a female voice speaks the individual digits or whole integers. Its large 8 digit LCD readout is ~ 0.6 in. (1.52 cm) high. The calculator can add, subtract, divide, multiply and calculate percentages. (Reproduced from Ref. 5.)

A quick check of electronic catalogs on the Internet shows that many types of independent living aids are available. For example, special clocks and timers that give both voice and vibratory alarms are available in various sizes and features. Other assistive devices for ADL include talking wrist watches, push-button padlocks, special money holders, Braille embossed large push button phones, and jumbo sized playing cards embossed with Braille. Personal care items for the blind include talking bathroom scales, thermometers, glucose monitors, blood pressure gauges, and prescription medicine organizers. Educational aids that facilitate note taking, calculating, searching, printing, and organizing information include talking calculators (Fig. 6), pen-like handheld scanner for storing text, letter writing guides with raised lines, Braille metal guides and styluses, and signature guides.

MOBILITY AIDS

For persons with severe visual impairments, the advent of powerful and affordable reading machines and the vast amount information (already in electronic form) on the internet, the problem of access to reading materials has been significantly ameliorated. In contrast, their other major problem (the ability to travel safely, comfortably, gracefully, and independently through the environment) has only been partially solved.

Despite years of effort and some major advances in technology, there is no widely accepted electronic travel aid (ETA). Most blind individuals rely on the sighted human guide, a guide dog, and the familiar white cane. The human sighted guide offers companionship, intelligence, wayfinding capability, route recall, and adaptability. Unfortunately, human guides are not always available, and their very presence constitutes a lack of independence. A guide dog or animal guide has been popular, but not every blind person can independently care for a living animal nor afford the cost of its care. In some social situations, a guide dog can be awkward or unacceptable. The white cane, which is both a tool and a symbol for the blind, can alert sight-impaired travelers to obstacles in their path, but only those at ground level and < 5 ft. (1.5 m) away. Above ground obstacles and especially those at head height remain a source of apprehension and danger for travelers depending on just the white cane.

To understand why decades of research and development efforts have not yielded an efficacious and widely accepted electronic travel aid, one needs to realize that mobility aids must deal with a very different set of constraints and inputs than do reading aids. An identification error made by reading aids results only in misinformation, mispronunciation, or inconvenience. In contrast, a failed detection of an obstacle or step-down or a missed landmark can lead to confusion, frustration, apprehension, and physical injury.

Another major difference between a mobility aid and a reading aid lies in their operating milieu. Mobility aids must detect and analyze unconstrained, long range, and highly variable environmental inputs, that is, obstacles of differing sizes, textures, and shapes distributed over a 180° wide area. In contrast reading machines must identify and convert into intelligible speech inputs that are often well defined and short ranged, for example, high contrast printed alphanumeric symbols and punctuation marks (15).

To further complicate matters, users of reading aids often have the luxury of focusing all or most of their attention on the task at hand: interpreting the output of the reading aid. Users of mobility aids, however, must divide their attention among several demanding tasks associated with traveling, such as avoiding obstacles, listening to environmental cues, monitoring their physical location, recalling the memorized route, and interpreting the auditory or tactile cues from their mobility aid. Given these challenges, today's mobility aids represent a much less satisfactory solution (in comparison to available reading aids) to the problem of independent and safe mobility for persons with severe visual impairments.

THE IDEAL MOBILITY AID

Before examining the capabilities of currently available mobility aids, it is desirable to enumerate the fundamental features of an ideal electronic travel or mobility aid (Table 2) (16–18). The first three items of an ideal mobility aid can be categorized as nearby obstacle avoidance; features 4–7 fall under the category of navigational guidance or wayfinding; and features 8–10 represent good ergonomic design or user friendliness.

CONVENTIONAL ELECTRONIC TRAVEL AIDS

Standard or conventional electronic travel aids detect nearby obstacles, but provide no wayfinding assistance. Obstacle detection entails the transmission of some sort of energy into the surrounding space and the detection of the reflections. After analyzing the reflected signals, the ETA warns the traveler of possible obstacles using either auditory feedback or tactile feedback.

Table 2. The Ideal Mobility Aid

	Capabilities and Features	Description
Feature No. 1	Obstacle detection	Detect nearby obstacles that are ahead, at head level, and at ground level and indicate their approximate locations and distances without causing sensory overload.
Feature No. 2	Warn of impending Obstacles	Reliably locate and warn of impending potholes, low obstacles, step-downs and step-ups.
Feature No. 3	Guidance around obstacles	Guide the traveler around impending obstacles.
Feature No. 4	Ergonomically designed	Offer voice and/or tactile feedback of traveler's present location. Capable of voice input operation and/or have tactually distinct push buttons
Feature No. 5	Wayfinding	Able to monitor the traveler's present location and indicate the direction toward the destination
Feature No. 6	Route recall	Be able to remember a previous route and warn of changes in the environment due to construction or other blockages
Feature No. 7	Operational flexibility	Reliably function in a variety of settings, that is, outdoors, indoors, stairways, elevators, and cluttered open spaces
Feature No. 8	User friendliness	Be portable, rugged, fail-safe, and affordable for a blind user
Feature No. 9	Cosmesis	Be perceived by potential users as cosmetically acceptable and comfortable to use in terms of size, styling, obtrusiveness, and attractiveness
Feature No. 10	Good battery life	Have rechargeable batteries that can last for at least 6 h per charge

The LASER CANE (Fig. 7) is one of the few conventional ETAs that can serve as a stand-alone, primary travel aid because it has obstacle detection (features 1–3 of Table 2) and is reasonably user friendly and cosmetic (features 8–10). The laser cane's shaft houses three narrow-beam lasers; the lasers scan upward, forward, and downward. Reflections from objects in these zones are detected by three optical receivers also housed in the shaft. The UP channel monitors head level obstacles and causes high pitched beeps to be emitted. The FORWARD channel monitors objects located 4–10 ft. (1.21–3.01 m) ahead of the cane's tip and produces warning signals in the form of either vibrations in the handle of the cane or a medium (1600 Hz) audio tone. Obstacles encountered by the DOWN channel produce a low frequency (200 Hz) warning tone (19). Because the laser cane is swept through an arc ~ 3–4 ft. (0.91–1.21 m) wide in the direction of the intended path (in a manner similar to standard long cane usage), the laser cane augments the auditory and tactile feedback of an ordinary white cane by detecting objects at greater distances and, most importantly, head level obstructions.

The laser cane's main drawbacks include it being somewhat costly and fragile. It also cannot monitor the traveler's geographic location nor guide the traveler toward the intended destination (features 5 and 6). Field tests and consumer feedback revealed that laser obstacle detection can be highly variable because certain surfaces and objects reflect laser light better than others. For example, the laser beam mostly passes through glass so that the laser cane may miss glass doors or large glass windows ahead.

Although the laser cane is imperfect, it has one major advantage as an ETA; It is failsafe. Should its batteries run down or its electronics malfunction, the laser cane can still serve as a standard long cane (20) and thus still be useful to the traveler.

Another commercially available electronic travel aid is the Sonic Guide, an eyeglass frame equipped with one ultrasonic transmitter and two receivers embedded in

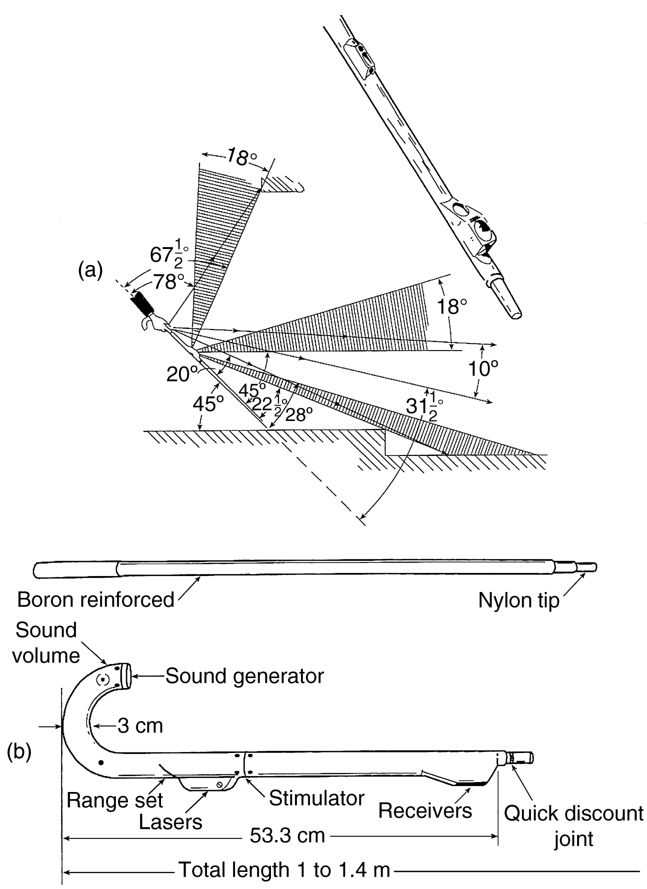

Figure 7. The laser cane projects three narrow beams of laser light. If any of the beams (up, forward, and downward) encounter an object and is reflected back to the receivers in the cane's shaft, a tactile or auditory warning is generated. (Reproduced from Ref. 19.)

the nose piece (21). The pulsed ultrasonic beam radiates through a forward solid angle of $\sim 100^{\circ}$. Objects in the environment reflect ultrasound back to the two receivers with time delays proportional to their distance and angle with respect to the wearer's head. The wearer is given awareness of his surroundings via binaural auditory feedback of the reflected signals, recreating the experience of echolocation as found in bats or dolphins. An object's distance is displayed in terms of frequencies proportional to the object's distance from the user. The azimuth of an object relative to the user's head is displayed via the relative intensity of tones sent to the ears (stereoscopic aural imaging). As a result, the binaural sounds heard by the user changes as he moves or turns his head.

To circumvent Sonic Guide's tendency to interfere with normal hearing, Kuc (22) investigated the utility of using vibrotactile feedback via a pair of sonar transceivers and vibrators worn on the wrists. Being on opposite sides of the body, the dual sonar transceivers offered better left–right obstacle discrimination than could a single sonar unit embedded in the nose piece of the eyeglasses. The wrist mounted pager-like device vibrated at a frequency inversely related to the reflecting object's distance from that side of the body.

Unfortunately, neither the original eyeglass frame based Sonic Guide nor the wrist worn sonar guide can serve as a stand-alone travel aid because neither can detect impending step-ups, step-downs, or other tripping hazards in the pathway. Other user comments about the Sonic Guide include interference with normal hearing, sensory overload, and difficulty in combining the aid's feedback with other important environmental cues such as the sound of traffic at street intersections, tactile feedback from a white cane, or the subtle pull of a guide dog.

In contrast to Sonic Guide's rich auditory feedback, the Mowat Sensor implements the design philosophy that simpler is better. The Mowat Sensor is a handheld ultrasonic flash light that acts like a clear path detector. It measures $6 \times 2 \times 1$ in. ($15 \times 5 \times 2.5$ cm), weighs 6.5 oz (184.2 g), can be easily carried in a pocket or purse, and is manufactured by Pulse Data International Ltd. of New Zealand and Australia.

The Mowat device emits a pulsed elliptical ultrasonic beam $\sim 15^{\circ}$ wide by 30° high, a beam pattern that should detect doorway sized openings located some 6 ft. (1.8 m) away. Reflections from objects in the beam pattern cause the Mowat to produce vibrations that are inversely proportional to the object's distance from the detector. As the traveler points at and gets closer to the object, the Mowat vibrates faster and faster. As the traveler aims moves away from that object, the vibrations slow and then cease. Objects outside of Mowat's beam pattern produce no vibrations.

The Sonic Guide, Mowat Sensor, and their various derivatives share similarities while representing two divergent design philosophies. They all employ ultrasound instead of laser light to detect nearby obstacles. None of them can detect tripping hazards, such as impending step-ups, step-downs, uneven concrete walkways, or small low obstacles in the path of travel so they cannot serve as a stand-alone travel aid. The Mowat sensor scans a small portion of the environment, displays limited data from that region, and offers easily interpreted vibratory information to the user. Alternatively, the Binaural Sonic Guide sends a broad sonic beam into much of the traveler's forward environment, displays large amounts of environmental information, and leaves it up to the user to select which portion of the auditory feedback to monitor and which to ignore.

While similar in concept, obstacle detection via ultrasound and obstacle detection via laser light interact with the environment differently. For example, hard vertical surfaces and glossy painted surfaces reflect sound and light very well so they tend to be detected by both methods at greater distances than oblique surfaces or dark cloth covered soft furnishings. Transparent glass, however, reflects sound very well, but laser light very poorly. Hence an ultrasonic beam would readily note the presence of a glass door whereas laser light could miss it entirely. Sonar based ETAs, however, are susceptible to spurious sources of ultrasound such as squealing air breaks on buses. Such sources and even heavy precipitation can cause the sonar sensor to signal the presence of a phantom obstacle or produce unreliable feedback. Furthermore, because all ETAs display environmental information via the sense of touch or hearing, severe environmental noise and wearing gloves or ear muffs can reduce a user's ability to monitor an ETAs feedback signals.

Other drawbacks of conventional electronic travel aids include the lack of navigational guidance (features 5 and 6 of Table 2), thus limiting the blind traveler to familiar places or necessitating directional guidance from a sighted guide until they have memorized the route. Furthermore, conventional ETAs often require the user to actively scan the environment and interpret the auditory and tactile feedback from the aids. These somewhat burdensome tasks require conscious effort and can slow walking speed.

INTELLIGENT ELECTRONIC TRAVEL AIDS

Recent advances in technology have sparked renewed efforts to develop mobility aids that address some of the aforementioned drawbacks. One promising intelligent electronic travel aid, under development at the University of Michigan Mobile Robotics Laboratory, is the GuideCane (23). The GuideCane (Fig. 8) is a semiautonomous robotic guide that improves user friendliness by obviating the burden of constant scanning while also guiding the traveler around obstacles, not merely detecting them. It consists of a self-propelled and servocontrolled mobile platform connected to a cane. An array of 10 ultrasonic sensors is mounted on the small platform. The sensors emit slightly overlapping signals to detect ground-level obstacles over a 120° arc ahead of the platform. The sonar units, made by Polaroid Corporation, emit short bursts of ultrasound and then uses the time of flight of the reflections to gauge the distance to the object. The sonar has a maximum range of 30 ft. (10 m) and an accuracy of $\sim 0.5\%$ (24).

When walking with the GuideCane, the user indicates his intended direction of travel via a thumb-operated mini-joystick mounted at the end of a cane attached to the

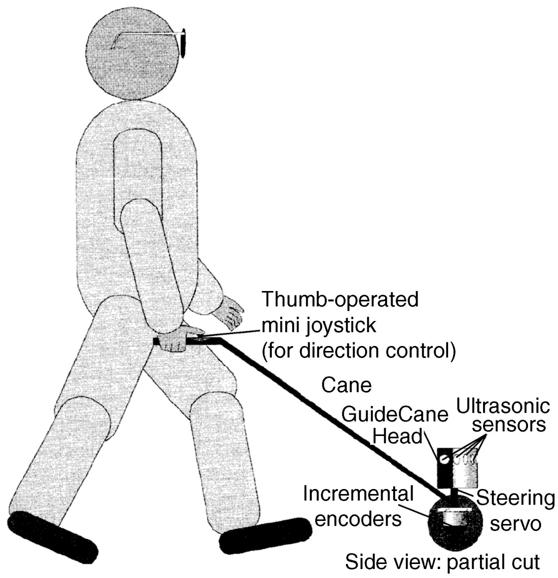

Figure 8. The GuideCane functions somewhat like a robotic guide dog. It is able to scan the environment and steer around obstacles by using its ultrasonic sensors, steering servomotors, and on-board computer to keeps track of nearby obstacles and the intended path of travel. (Reprinted from figure on p. 435 of Ref. 23.)

platform. The mobile platform maintains a map of its immediate surroundings and self-propels along the indicated direction of travel until it detects an obstacle at which time the robotic guide steers itself around it. The blind traveler senses the GuideCane's change of direction and follows it accordingly.

Like the Laser cane, the GuideCane can function as a stand-alone travel aid because it gives advance warning of impending step-downs and tripping hazards. Its bank of 10 ultrasonic detectors and ability to navigate around detected obstacles make the GuideCane easier and less mentally taxing to use than the Laser Cane. To address the wayfinding needs of the blind traveler, efforts are underway to add GPS capability, routing software and area maps to the GuideCane. The drawbacks of the wheel mounted GuideCane, however, include its size and weight and its inability to detect head height objects.

NAVIGATIONAL NEEDS

Electronic travel aids like those described above are becoming proficient at detecting and enabling the traveler to avoid obstacles and other potential hazards. Avoiding obstacles, however, represents only a partial solution to a blind person's mobility problem. Many visually impaired or blind travelers hesitate to visit unfamiliar places because they fear encountering an emergency or possibly getting lost. Their freedom of travel is hampered by having to pre-plan their initial trip to a new place or needing to enlist the help of a sighted person.

Furthermore, blind pedestrians, even those with training in orientation and mobility, often experience difficulty in unfamiliar areas and areas with free flowing traffic, such as parking lots, open spaces, shopping malls, bus terminals, school campuses, and roadways or sidewalks under construction. They also have difficulty crossing nonorthogonal, multiway traffic intersections (25). Conventional traffic signals combined with audible pedestrian traffic signals have proven somewhat helpful in reducing the pedestrian accident rates at intersections (26–28), but audible traffic signals offer guidance only at traffic intersections and not other important landmarks.

One proposed solution for meeting the wayfinding needs of blind travelers is the Talking Sign, a remote infrared signage technology that has been under development and testing at The Smith-Kettlewell Eye Research Institute in San Francisco, CA (29,30). The Talking Signs system consists of strategically located modules that transmit environmental speech messages to small, hand held receivers carried by blind travelers (Fig. 9). The repeating and directionally selective voice messages are transmitted to the receiver by infrared (IR) light (940 nm, 25 kHz). Guided by these orientation aids, blind travelers can know their present location and move in the direction from which the desired message, for example, Corner of Front Street and Main Street, is being broadcasted, thus finding their way without having to remember the precise route.

The Talking Sign and other permanently mounted voice output devices, however, require standardization, costly retrofitting of existing buildings, and the possession of a suitable transceiver to detect or activate the installed devices. Retrofitting buildings with such devices is not cost effective due to their inherent inflexibility and the need for many users to justify the implementation costs. What's especially frustrating for persons with severe visual impairments is that talking signs may not reflect their travel patterns or be available at unfamiliar locations and wide open spaces. To be truly useful, talking signs would have to be almost ubiquitous and universally adopted.

GPS NAVIGATIONAL AIDS

In addition to obstacle avoidance, the ideal navigational aid also must address two other key aspects of independent travel: orientation (the ability to monitor one's position in relationship to the environment) and route guidance (the ability to determine a safe and appropriate route for reaching one's destination). As an orientation aid, the Global Positioning System (GPS) seems promising. For route guidance, a notebook computer or personal data assistant (PDA) equipped with speech input/output software, route planning software (artificial intelligence), and digital maps have been proposed (18,31,32). A voice operable, handheld GPS unit used in combination with obstacle detecting ETAs like the Laser Cane might constitute the ideal navigational aid for blind persons.

Several GPS equipped PDAs have recently become available. For example, the iQue 3600 ($600 from Garmin International Inc., Olathe, Kansas) is a handheld device that combines a PDA and mapping software with a built-in GPS receiver. The iQue 3600 uses the Palm operating system and offers a color screen and voice output turn-by-turn navigational guidance. For someone who already possesses a PDA (e.g., Palm Pilot or Microsoft's Pocket

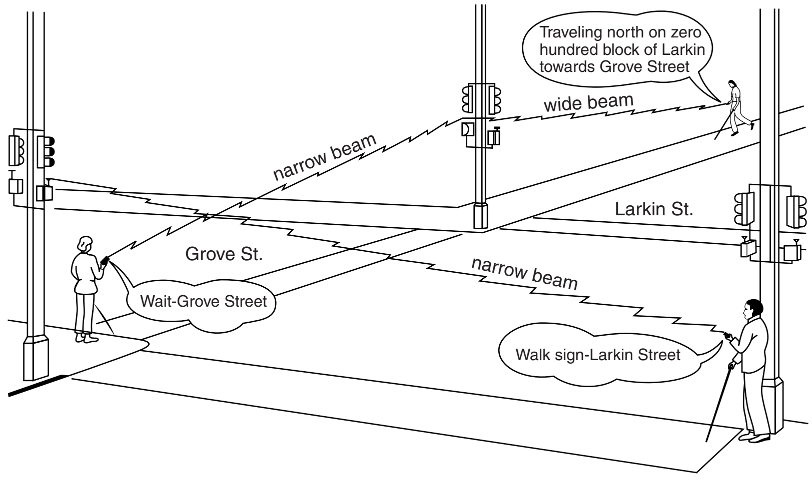

Figure 9. Talking Signs not only gives location information, but also tells the pedestrian the current status of the pedestrian cycle, aids in finding the cross-walk, and indicates the direction of the destination corner. (Reproduced from Ref. 29.)

PC), various third party software and GPS add-on units can be used.

While promising as a navigational aid for persons with severe visual impairments, GPS equipped portable PDAs (or notebook computers) have significant limitations. To fully appreciate these limitations, a brief review of how the Global Positioning System works (Fig. 10) would be apropos.

Global Positioning System (GPS) began some 30 years ago when Aerospace Corporation in Southern California studied ways to improve radio navigation systems for the military (33). Although GPS was not fully operational at the outbreak of the Persian Gulf War in January 1991, its exceptional performance in accurately locating fighting units evoked a strong demand from the military for its immediate completion.

Currently, 24 satellites of the GPS circle the earth every 12 h at a height of 20,200 km. Each satellite continuously transmits pseudorandom codes at 1575.42 and 1227.6 MHz. The orbital paths of the satellites and their altitude enable an unobstructed observer to see between five and eight satellites from any point on the earth. Signals from different visible satellites arrive at the GPS receiver with different time delays. The time delay needed to achieve coherence between the satellites' pseudorandom codes and the receiver's internally generated code equals the time-of-flight delay from a given satellite. GPS signals from at least four satellites are analyzed to determine the receiver's longitude, latitude, altitude (as measured from earth's center) and the user's clock error with respect to system time (33).

For civilian applications, position accuracy of a single channel receiver is about 100 m and its time accuracy is ~ 340 ns. Greater accuracy, usually within 1 m, can be achieved using differential GPS wherein signals from additional satellites are analyzed and/or the satellite signals are compared with and corrected by a GPS transceiver at a known fixed location (33).

At first glance, GPS signals seem fully able to meet the orientation needs of persons with severe visual impairments. The GPS signals are sufficiently accurate if combined with differential GPS and signals are immune to weather and are available at any time of the day, anywhere there's a line of sight to at least four GPS satellites. Lastly, a GPS receiver is relatively inexpensive, $< \$200$.

Unfortunately, just equipping blind persons with a voice-output GPS receiver for wayfinding outdoors is insufficient. The GPS signals are often unavailable or highly attenuated under bridges, inside natural canyons, and between tall buildings in urban areas. The altitude GPS information is generally not useful, and its longitudinal and latitudinal coordinates are useless when unaccompanied by local area maps (17). For college campuses or even major metropolitan areas, the location of major buildings and their entrances in terms of longitude and latitude coordinates are rarely available. Without these key pieces

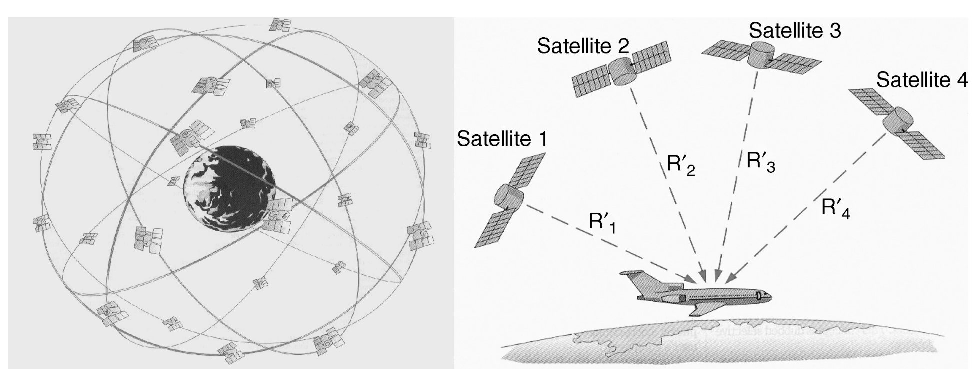

Figure 10. Synchronized signals from four satellites are analyzed by the mobile receiver to determine its precise position in three dimensions. The distances for the four satellites include an unknown error due to the inaccuracy of the receiver's clock and Doppler effects. (Reprinted from Ref. 33.)

of information, the GPS navigational aid is unable to offer directional guidance to the blind traveler.

INDOOR NAVIGATIONAL AIDS

One of the key characteristics of an ideal mobility aid is that the device reliably function indoors, outdoors, and within changing environments (Table 2). When used in combination with detailed local area maps, the GPS receiver and voice output could form the basis for a navigational aid. However, GPS signals may not be available at all times and are totally absent indoors. To function indoors, an electronic navigational aid will need to rely on some other set of electronic beacons as signposts.

For wayfinding within a large building, several investigators have borrowed the idea found in the Hansel and Gretel fairy tale about two children leaving a trail of bread crumbs to find their way home again. Instead of bread crumbs, Szeto (18) proposed placing small, low cost electronic beacons along corridors or at strategic locations (e.g., elevators, bathrooms, stairs) of buildings visited. Acting like personal pathmarkers, these radio frequency (RF) emitting electronic beacons would be detected by the associated navigational aid and guide the traveler back to a previous location or exit. To avoid confusion with other users, the electronic beacons could be keyed to work with one navigational aid.

Kulyukin et al. (34) recently studied the efficacy of using Radio Frequency Identification (RFID) tags in robot-assisted indoor navigational for the visually impaired. They described how strategically located, passive (nonpowered) RFID tags could be detected and identified by a RFID reader employing a square 200×200 mm antenna and linked to a laptop computer. In field tests, wall-mounted RFID tags responded to the spherical electromagnetic field from an RFID antenna at a distance of ~ 1.5 m. Since each tag is given a unique identifier, its location inside a building can be easily recalled and used to locate one's position inside a building.

In comparison to wall-mounted Talking Signs, the approach of Szeto (18) and Kulukin et al. (34) seems to be less costly and more flexible. Placing disposable electronic beacons in the hands of individual travelers does not require permanent retrofits of buildings, can be cost effective even for single users, and easily changes with the travel patterns of the user.

The electronic beacons and handheld electronic transceivers also should be economically feasible because they utilize a technology that's being developed for the mass market. World's largest retailer, Wal-Mart, has mandated 2008 as the year when all its suppliers must implement an RFID tracking system for their deliveries. It is likely that RFID tags, antenna, and handheld interrogators developed for inventory tracking can be adapted for use in an indoor navigational aid.

Although not yet a reality, a low cost, portable, handheld, indoor–outdoor mobility aid that embodies many of the features listed in Table 2 is clearly feasible. The needed technological infrastructure will soon be in place. For obstacle avoidance, the Laser Cane, Guide Cane, or their variants can be used. For indoor wayfinding and route guidance, the blind traveler could augment the cane or guide dog with a handheld voice output electronic navigational aid linked to strategically placed electronic beacons. For outdoor wayfinding, the blind traveler could augment the Laser Cane with a handheld mobility aid equipped with a GPS receiver, compass, local area maps, and wireless internet link.

The intelligent navigational aid just described would address the mobility needs of the blind by responding to voice commands; automatically detecting GPS signals or searching for the presence of electronic beacons; wirelessly linking to the local area network to obtain directory information; converting the GPS coordinates or the signals from electronic beacons into a specific location on a digital map; and, with the help of routing finding software, generating step-by-step directions to the desired destination.

FUTURE POSSIBILITIES

Of course, the ultimate assistive technology for overcoming the many problems of severe visual impairment would be an artificial eye. Since the mid-1990s, research by engineers, ophthalmologists, and biologists to develop a bionic eye have grown and artificial retina prototypes are nearing animal testing. An artificial eye would incorporate a small video camera to capture light from objects and transmit the image to a wallet-sized computer processor that in turn sends the image to an implant that would stimulate either the retina (35) or visual cortex (36).

Researchers at Stanford University recently announced progress toward an artificial vision system that can stimulate a retina with enough resolution to enable a visually impaired person to orient themselves toward objects, identify faces, watch television, read large fonts, and live independently (37). Their optoelectronic retinal prosthesis system is expected to stimulate the retina with resolution corresponding to a visual acuity of 20/80 by employing 2500 pixels per square millimeter. The researchers see the device as being particularly helpful for people left blind by retinal degeneration. Although such developments are exciting, tests with human subjects on practical but experimental prototypes won't likely occur for another 6–8 years (38).

What else the does the future hold in terms of assistive technology in general and mobility aids in particular? In an address to the CSUN 18th Annual Conference on Technology and Persons with Disabilities in 2003, futurist and U.S. National Medal of Technology recipient, Ray Kurzweil, presented his vision of the sweeping technological changes that he expected to take place over the next few decades (39). His comments are worthy of reflection and give cause for optimism.

With scientific and technological progress doubling every decade, Kurzweil envisions ubiquitous computers with always-on Internet connections, systems that would allow people to fully immerse themselves in virtual environments, and artificial intelligence embedded into Web sites by 2010. Kurzweil (39) expects the human brain to be fully reverse-engineered by 2020, which would result in computers with enough power to equal human intelligence. He forecasted the emergence of systems that provide subtitles for deaf people around the world, as well as listening systems geared toward hearing-impaired users. Blind people would be able to take advantage of pocket-sized reading devices within a decade or have retinal implants that restore useful vision in 10–20 years. Kurzweil believed that people with spinal cord injuries would be able to resume fully functional lives by 2020, either through the development of exoskeletal robotic systems or techniques that bridged severed neural pathways, possibly by wirelessly transmitting nerve impulses to muscles. Even if one-half of what Kurzweil predicted became reality, the future of assistive technology for the blind is bright and an efficacious intelligent mobility aid for such persons will soon be commercially available.

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See also COMMUNICATION DEVICES; ENVIRONMENTAL CONTROL; MOBILITY AIDS; VISUAL PROSTHESES.