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### Summary

Two main problems to be solved in designing truly effective mobility aids for the blind are:  
(1) to determine what kinds and how many pieces of information are necessary and/or sufficient to mobilize humans, and  
(2) to establish the optimal coding and display method of thus acquired information.

Our laboratory has been working on the MELDOG project which intends to enhance mobility aids for the blind by providing them with the functions of guide dogs, i.e., obedience in navigating or guiding its blind master, intelligent disobedience in detecting and avoiding obstacles in his path, and superb man-machine (animal) companionship or communication.

If the robot can independently travel from one place to another using a city map with specified landmarks stored in the memory of the robot and the obstacle information gathered by the sensors on board the robot, these pieces of information acquired and used by the robot provide one solution to the first problem.

For the second problem of displaying the information acquired, electrocutaneous communication systems have been developed based on the fundamental experiments on electrocutaneous stimulation. These include constant pulse energy circuits which keep the perceived sensational magnitude constant despite the change of the skin impedance and two-dimensional phantom sensations which reduce the number of the electrodes used with the enhancement of the sensation of motion.

### Introduction

Strong desire for mobility aids for the blind which ensure independent travel exists among more than three hundred and forty thousand blind or severely visually impaired individuals in Japan.

Little theoretical research has been done on the processes of mobility, i.e., what are the necessary and/or sufficient pieces of information about the surroundings that enable normal human mobility possible. Mann broke down mobility processes into three functions: (1) the blind person's next step, (2) his/her directional orientation, and (3) his/her navigation along reasonably long travel paths on both familiar and unfamiliar terrain [1].

Although ideal mobility aids for the blind should have these three functions, existing mobility devices at the stage of significant evaluation, namely, the Pathsounder[2], the Sonic Glasses[3], the Laser Cane [4,5], the Mowat Sensor[6] and the Nottingham Obstacle

Detector[7], have only the functions of (1) and (2). As for the functions of (1) and (2), the information processing system employed by them is very simple and crude, so that the blind user must concentrate on the devices, resulting in the fatigue of the user or loss of other information which otherwise might be obtained through the remaining senses.

With the advent of recent electronic technological break-through, it is becoming possible to design more intelligent mobility aids for the blind which combine the above three functions with the enhancement of the functions of (1) and (2) by increasing the information processed by the device or the machine. These devices warn only if the blind persons are in danger, thereby not distracting the attention of the blind traveler from other potential cues through their remaining senses. This design concept of supervisory systems [8] is very similar to the traveling style with a guide dog (Seeing Eye).

Our laboratory started a six year project called MELDOG in the fiscal year of 1977 to enhance the mobility aids for the blind by providing them with the functions of guide dogs, i.e., obedience in navigating or guiding its blind master, intelligent disobedience in detecting and avoiding obstacles in his/her path, and the well-organized man-machine (animal) communication which does not interfere his/her remaining senses.

In this paper the design concept of MELDOG and some experimental results with the test hardware (MARK I, II and III) are discussed. Special emphasis is put on the electrocutaneous communication system which is or will be used in MELDOG. Experimental results of the electrocutaneous communication per se which are the bases of the system design are also discussed.

### Guide Dog Robot

Two main problems to be solved in designing truly effective mobility aids for the blind are:  
(I) theoretical understanding of human mobility (normal and blind) analogous to the elucidation that linguistics reading and speech research provide on human language and communication, e.g., to determine what kinds and how many pieces of information are necessary and/or sufficient to mobilize humans, and  
(II) to establish the optimal coding and display method of thus acquired information.

In an effort to gain more understanding of the process of mobility, whether of a blind or sighted traveler, a mathematical model of the mobility process was proposed [9]. The analytical model proposed treated a traveler as a processor of information which was gathered with a probe, was used for path traversal, and was lost in the uncertainties of memory, decay, and

disorientation. The basis for the model is an equation that balances information gains and losses.

Another approach may be through analysis by synthesis. If a robot can independently travel from one place to another using a city map with specified landmarks stored in the memory of the robot and obstacle information gathered by the sensors on board the robot, these pieces of information acquired and used by the robot are one solution to the problem (I). MELDOG approaches this problem of mobility in this manner.

Functionally, mobility can be broken down into (1) next step, (2) orientation, and (3) navigation. It is common to think of these functions in this order. When we observe, however, the training process of guide dogs, these functions are in reverse order, i.e., obedience, which corresponds to the guidance or navigation of the blind master, comes first, and then intelligent disobedience, which corresponds to the obstacle detection and avoidance, comes next. In the design of the guide dog robot, function (3) was considered first.

The fundamental data base of the robot is its navigation map stored in the auxiliary memory, e.g., cassette tapes, and transferred into the main memory of the robot when in use. The navigation map consists of the information about intersections, i.e., names and types of intersections, distance between two adjacent intersections, and orientation to the adjacent intersections. In other words, for the first order approximation, we adopted John Kenneth Dupress's travel style of identification of the unobstructed tunnel that would permit the traveler's safe transport through the surrounding space [1]. Information as to the kind of shops which exist along the street is not essential. Only the relations among intersections are essential. The navigation map appears as tunnels that connect intersections. This connection map is represented as an automaton [8].

The next step the robot should take is to identify the real intersection which is specified on the map and correct its position and orientation so that it can travel farther. In order to do so, specific landmarks are chosen for each intersection. Although it is quite desirable to use natural landmarks, such as buildings, poles, trees, etc., technological limitation forced us

to use artificial landmarks as our first approach. We adopted white painted lines on the streets with a length of about 2m and width of about 0.15m as our landmark. We must set these marks at every crossing at this stage of development. The automaton representation map for the robot can be automatically made by an off-line computer from an ordinary map using picture processing techniques. Landmark laying instructions which will be used to place the landmarks on the streets can be made at the same time.

With this predetermined map on board the robot, the guide dog robot (1) navigates, (2) orients, and (3) solves the next step as follows (Photo. 1) :

- (1) In principle, the master takes the initiative. The master orders the robot by control switches through a wired link. The robot proceeds the master and stops on each landmark which is set at every crossing, and waits for the master's next order (right, left, straight, or stop) and obeys it. If the master does not know the area and wants full automatic guidance, all he has to do is to assign the starting code and the destination code. The robot determines whether there is a route to reach the destination. If plural routes exist, it chooses an optimal route and guides the master accordingly [10] (Fig.1 Landmark Subsystem).
- (2) In normal travel, the speed of the robot is controlled so that it coincides with that of the master's walk. Thus if the master walks slowly or quickly, the robot also moves slowly or quickly, keeping the distance between them almost constant. As long as the master is considered to be safe by the robot he is not warned, so that he may concentrate on his remaining senses and his own decision. Only when he fails to detect an obstacle or is out of the safety zone, he is warned by the robot [11] (Fig.1 Man-Machine Communication Subsystem).
- (3) When the robot detects a dangerous situation on the road, it no longer obeys the master's command but gives him a warning. If the obstacle is moving toward the master, it stops and alerts the moving object and the master. If the obstacle is moving in the same direction but slower than the master, it asks the master to reduce speed to follow the preceding object, probably a human traveler. If something is crossing in front of the robot, the robot waits till it passes. If it detects obstacles which do not move, it tries to determine if it is possible to find space (or tunnel) that will permit the safe transport of the master's

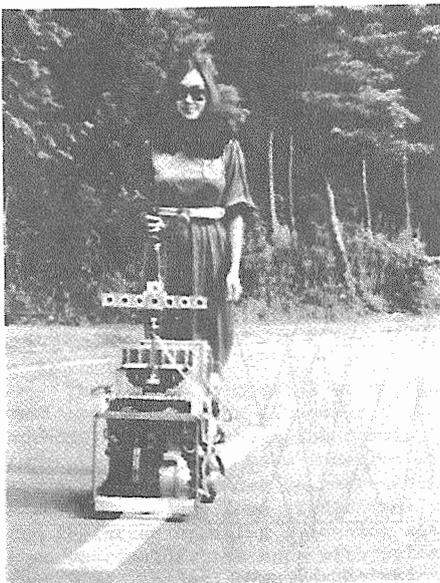


Photo. 1. General view of the guide dog robot MELDOG MARK III.

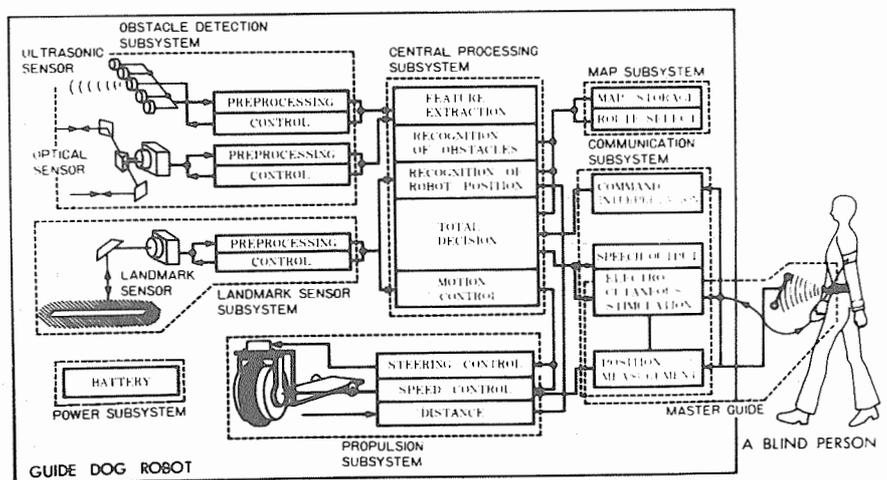


Fig. 1. Schematic diagram of the guide dog robot system (MELDOG).

body around the obstacle. If space exists, it guides the master around the obstacle to the next landmark safely. If not, it tries to find a new route to the destination without using that path [8] (Fig.1 obstacle Detection Subsystem).

#### Tactile Communication System in MELDOG

The second problem in designing optimal mobility aids is to find the best coding and the display method of the acquired information. Mann proposed the 'mobility simulator' to study the systematic design of mobility aids as early as in 1965 [12], and it is now in operation at M.I.T. [13] and at our laboratory.

MELDOG also has the capability of systematic study of mobility information as it acquires sufficient information for mobility and passes it to the master via man-machine communication subsystem. The choice of the communication methods (coding and display scheme) is versatile. The test hardware carries a versatile micro-processor (LSI 11/02), which can be used as a display device emulator. It can also measure the movement of the master using the ultrasonic sensors on board the robot to determine the relative position and orientation of the master. Thus we can determine the optimal display scheme of the acquired knowledge using the master's behavior as its criterion of optimality.

We have been working on the use of the electrocutaneous communication systems because of their potential advantage of small size, light weight, low power consumption, silence, fixability to the human anatomy as compared to vibro-tactile display systems. As for the speech output, we are planning to use it when the information transmitted should be heard both by the master and other pedestrians and/or drivers passing by. If the master wants private communication with the robot, the electrocutaneous communication would be preferred. It will not interfere with the most reliable remaining sense, i.e. hearing.

#### Fundamental Experiments on Electrocutaneous Stimulation

Various investigations of electrocutaneous communication systems and studies on human characteristics to electrocutaneous stimulation have been conducted for the applications to the various fields, including the augmentation, substitution, and replacement of human sensory functions using the cutaneous sense as an auxiliary or alternative sensory communication channel from devices/machines to humans [14,15,16,17,18,19,20,21,22,23,24]. These are, quite simply, informative displays that utilizes the skin senses as an input channel to the human by passing small currents through the skin from external electrodes. The authors have been systematically studying the electrocutaneous sensation which is elicited by monopolar pulse trains to identify the relevant parameters of electrocutaneous stimuli-response system by means of computer controlled psychophysical experimentation. It is an effort to determine what physical stimulus parameters, e.g., pulse height, pulse width, pulse interval, and spatial configuration, relate with human response parameters or informative dimensions of display, e.g., perceived magnitude (loudness), perceived frequency (pitch), and perceived location of sensation including the location of phantom image produced by the simultaneous stimulation of plural channels. The capacity of the human electrocutaneous channel has also been determined both for each informative dimension of display and for combinations of independent display dimensions.

Generally in the transmission of information by the electrocutaneous stimuli, the signal is transmitted

in the form of a pulse train. Preliminary experiments revealed that negative monopolar pulse trains applied through wet electrodes, e.g. Beckman type, are the most suitable to study the relation between the physical parameters and informative dimensions. Dry electrodes cause burning pain sensation and the impedance between the electrode and skin can easily be changed by uncontrollable factors like sweating and pressure. Bipolar pulse trains contain too much physical parameters to identify the basic relationship between stimulus and response. Sensation elicited by the negative monopolar pulse trains applied through wet electrodes is fairly comfortable and the cutaneous sensation is quite consistent.

Considering from the analogy of hearing, loudness, pitch and location of the received stimulus can be used as independent informative dimensions of display. Pitch roughly corresponds to the pulse repetition rate (reciprocal of pulse interval), and location corresponds to the positions where the sensation occur. For loudness (perceived sensational magnitude), however, the correspondance is not that simple. Both pulse widths and pulse heights contribute to the perceived magnitude sensation, and it is essential to know their mutual effects. Both current and voltage can be the pulse height parameter, but in order to measure the pulse height and width precisely, current is superior to voltage as the height parameter because the skin impedance consists primarily of capacitance and resistance.

#### Perceived magnitude sensation

In order to investigate the interference between pulse height and pulse width, two pulse trains which have the same pulse interval and stimulus duration time but have the different pulse heights (IA and IB) and pulse widths (TA and TB) were presented on the human skin just above the triceps brachii through wet electrodes (Beckman 8mm). The CCS was used, and the pulse height was measured in mA.

The difference of the stimulus A and the stimulus

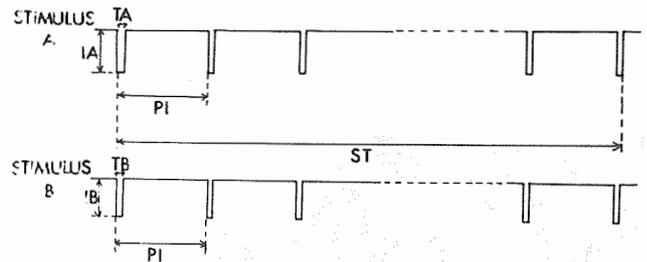


Fig. 2. Electrocutaneous stimuli A and B.

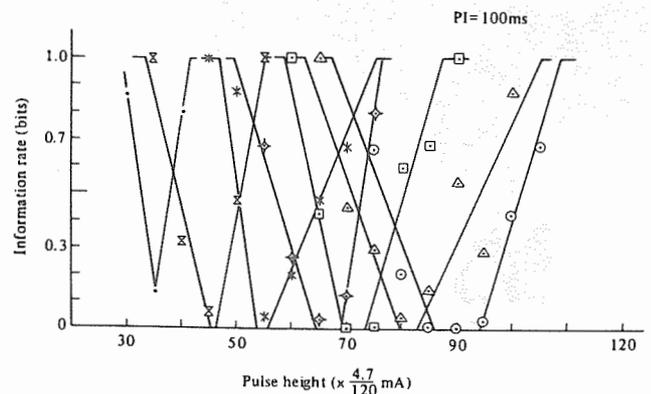


Fig. 3. Detectable difference between A and B.

B in Fig. 2 were judged by human subjects using the AB method. The stimulus A, the reference, had the fixed pulse height of  $I_A = 4.7$  mA, the pulse width of  $T_A = 100\mu\text{s}$ , and the stimulus duration time of  $ST = 2$  s. The pulse interval PI was selected as 100, 50, 20, and 10 ms for each round of the experiment. The same PI and ST values as of the signal A were set for the signal B. Each of the seven values of the signal B's pulse widths, i.e.,  $T_B = 150, 200, 250, 300, 400, 800,$  or  $1600\mu\text{s}$ , was assigned to the signal B. For each of the  $T_B$  values, one of the several arbitrary current values was selected for IB to complete the signal B. All possible combinations of the pulse height IB and the pulse width  $T_B$  were selected, and each of the stimuli B's thus formed was compared with the reference stimulus A. Either of the stimulus A or B is presented fifty times to human subjects and was judged which of the stimuli was presented. The information transmitted per stimulus was measured by means of the AB method, and it was used as the measure of the discriminability of the two stimuli. Figure 3 shows an example of the experimental results. Each mark in the figure is the result calculated from 50 times judgements, and the marks  $\circ, \Delta, \square, \diamond, *, \times,$  and  $\cdot$  indicate the results for  $T_B$  of 150, 200, 300, 400, 800, and  $1600\mu\text{s}$ , respectively. The abscissa represents IB, and the ordinate represents the information on the stimulus difference transmitted per stimulus in bit.

The discrimination curve for each pulse width is v-shaped, which means that there is certain condition that makes the discrimination of the two stimuli impossible. In other words IB values at the bottom of the v-shaped discrimination curves for several  $T_B$  values represent the condition that the stimulus B has the same perceived magnitude as that of the stimulus A.

In order to clarify the condition, the IB values that give the minimum discrimination for various  $T_B$  values are plotted using a log-log scale as a function of  $T_B$  (Fig. 4). The marks  $\circ, \times, \Delta,$  and  $\square$  are the results for PI = 100, 50, 20, and 10 ms, respectively, and each mark is the averaged value for three subjects. The solid line is the least means square approximation of the results when the results with  $T_B$  of less than 1 ms are considered. The gradient of the line is - 0.5.

Thus, when  $\log I_B = -0.5 \log T_B + k'$  holds, i.e.,  $I_B = kT_B^{-0.5}$ , or  $I_B^2 T_B = c = I_A^2 T_A$ , the perceived magnitude of the stimulus B is the same as that of the stimulus A. As impedance of the skin and tissue is thought to remain constant during relatively short period as one round of the experiment, the condition of the equal perceived sensational magnitude, i.e.,

$$I_A^2 T_A = I_B^2 T_B, \text{ can be interpreted as follows:}$$

$$Z I_A^2 T_A = Z I_B^2 T_B \quad \dots (1)$$

, where  $Z$  is the impedance of the tissue and the electrode.

The quantity  $Z I^2 T$  is an energy of the pulse. The condition might be [25]:

$$\int_0^T Z I_A(t)^2 dt = \int_0^T Z I_B(t)^2 dt, \quad T < 1 \text{ ms} \quad \dots (2)$$

The threshold current of minimum sensation for various pulse widths is measured by using the AB method. Figure 5 shows the result, where threshold current is measured as a function of pulse width  $T$ . The shape of the curve can be represented by the equation  $I = a + b/T$ , as has been traditionally done. These data are replotted by using a log-log scale as in Fig. 6. when we consider the data with pulse widths of less than 1 ms, the relation can be approximated by the straight line with the gradient of -0.6. This also suggests that the threshold of minimum sensation is obtained when the quantity  $I T^2$  becomes the same

constant value, or constant energy.

These findings [25] support the view of Green [27] that the energy is the most relevant parameter for the absolute threshold. These findings that the pulse energy is the most relevant parameter for the perceived magnitude sensation when the pulse width is less than 1 ms strongly suggest that the fine structure of the pulse within 1 ms would not affect much on the perceived magnitude sensation but its total energy within 1 ms would do effect.

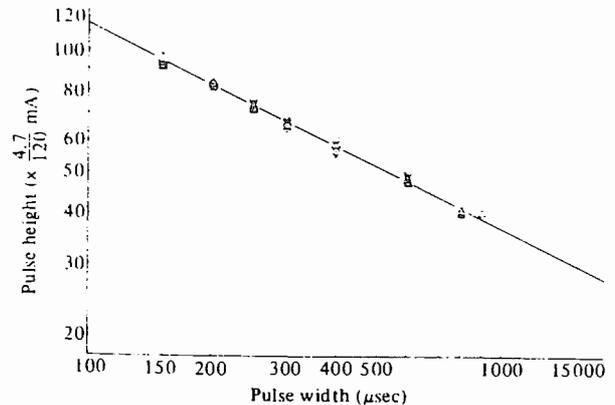


Fig. 4.  $I_B^2 T_B = I_A^2 T_A = \text{constant}$ .

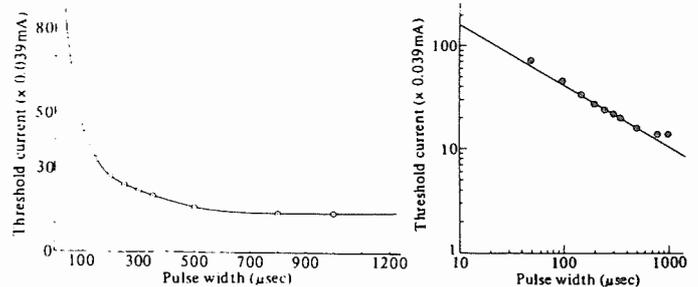


Fig. 5. Threshold current. Fig. 6. Replot of Fig. 5. Channel Capacity

The channel capacity of a magnitude information transmission system was measured [27] by using the constant energy stimulator designed [28]. The channel capacity was calculated using the following formula:

$$R = \log_2 \int_{\min E}^{\max E} \frac{1}{\Delta E(E)} dE \quad \dots (3)$$

, where  $\Delta E(E)$  is the just noticeable difference measured as a function of energy  $E$ , and  $\min E$  and  $\max E$  are the energies that give the minimum and maximum thresholds of perceived magnitude, respectively. The channel capacity is 3.0 to 4.0 bits per symbol.

The channel capacity of a pitch information transmission system was calculated using jud's measured as a function of frequency, and the maximum information transmission rate was estimated from the results of forced choice tests. The channel capacity is 2.5 to 3.0

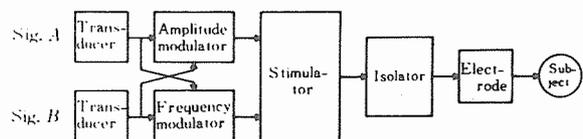


Fig. 7. Two-variable information transmission system.

bits per symbol in the frequency range of 10 pps to 100 pps. The maximum information transmission rate is about 2.1 bits per symbol, which is a little larger than the corresponding value for the magnitude dimension of 1.7 to 1.9 bits per symbol [29].

Two-variable display systems where two aspects of the stimulation, i.e., perceived magnitude and pitch sensation were used simultaneously were studied [30]. Figure 7 shows a typical two-variable electrocutaneous information transmission system which transmits two sorts of information. The problem of this type of display is that these two variables are not independent, i.e., magnitude sensation is affected by the change of frequency and vice versa. The solution of the problem is to change pulse energies along the equal magnitude sensation curves and pulse repetition rates along the equal pitch sensation curves. The latter effect, however, can be neglected. Figure 8 shows the equal magnitude sensation curves for electrocutaneous stimulation. Each dotted line in the figure indicates the difference limen from the corresponding equal magnitude curve. The channel capacity of a two-variable electrocutaneous information transmission system is estimated from the number of cross points of equal magnitude curves and equal pitch sensation lines. Its value ranges from 5.6 to 6.0 bits per symbol. The maximum information transmission rate estimated from the forced choice test is 2.7 to 3.2 bits per symbol [30].

A display that utilizes the cutaneous phantom sensation is interesting. Two equally loud electrocutaneous stimuli simultaneously presented to adjacent locations on the skin are not felt separately but rather combine to form a sensation midway between the two electrodes, just as in the case of binaural sound localization in hearing and the vibration phantom sensation on the skin. This phantom location can be controlled by relative magnitudes of the two stimuli and by the time delay between them [31]. Thus the number of electrodes can be reduced by using this phantom sensation display in comparison to a display requiring a discrete electrode for each position desired. The channel capacity of a location information transmission system using the phantom sensation depends on the distance  $d$  between the two electrodes and ranges from 2.0 to 3.0 bits for  $d$  between 50 and 150 mm [31].

Figure 9 shows the two-dimensional extension of this phantom display. The phantom image by three sets of electrodes (Fig. 9(a)) is the basis of the two-dimensional display because phantom display areas can easily be extended as in Fig. 9(b). Figure 10 shows

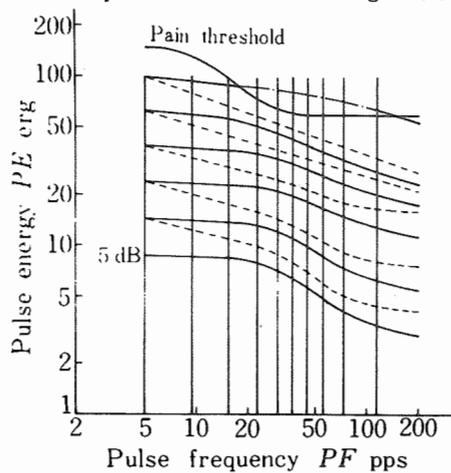


Fig. 8. Equal magnitude curves and equal frequency sensation lines.

the experimental arrangement used. The channel capacity of a two-dimensional phantom location information transmission channel is estimated to be about 4 bits per symbol from the jnd's of the perceived location. The maximum information transmission rate is about 2.8 bits per symbol [32].

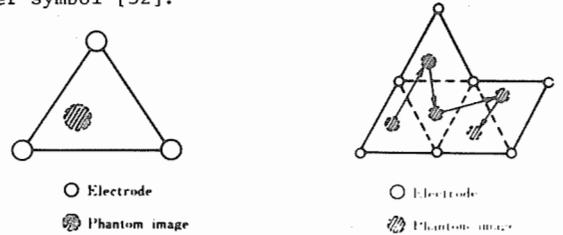
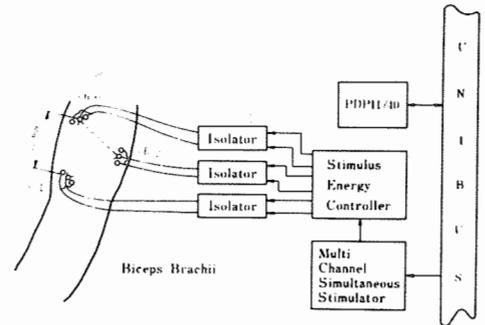


Fig. 9(a).

Fig. 9(b).

Fig. 10. Two-dimensional phantom sensation.



Master Guide

In MELDOG system the location of the master is measured by the robot in real-time by the triangulation among the ultrasonic oscillator put on the belt of the master and two receivers on board the robot. The speed of the robot is controlled by the walking speed of the master. The safety zone is set behind the robot, in which the master is permitted to walk. When he is out of the zone, he is warned by the robot, while he receives nothing when he is safe. When the orientation of the master is not appropriate, the Master Guide detects the condition and informs the master about it. These signals are transmitted through the wired link and presented to the master in the form of electrocutaneous stimulation on the skin. Two sets of Ag-AgCl wet electrodes are located on the skin of both brachia. The signals used are pulse trains with pulse width of about 100µs, the energy of which is controlled by the circuit shown in Fig. 11. The voltage across the electrodes and the pulse current are

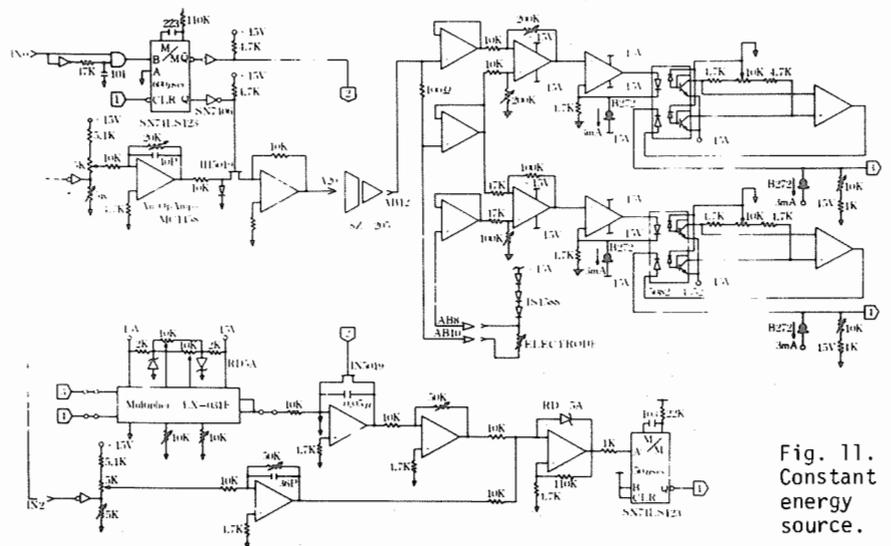


Fig. 11. Constant energy source.

measured, multiplied and integrated to be compared with the desired pulse energy. The monostable multivibrator is reset immediately to control the energy of the pulse by controlling the pulse width. The pulse current can be set automatically to a value proportional to the desired energy so that the controlled pulse width becomes always about 100 $\mu$ s.

#### Future studies

When a device which directs or guides a blind individual has somehow acquired information about the direction of, and width of, the path along which it should lead the blind individual, the problem is the choice of sensory display of the path and its safe margins appropriate for presentation to the remaining exterior receptive senses of the blind individual. A method for the quantitative comparison of display schemes has been proposed and an optimal auditory display scheme has been sought [13]. We are now working on the quantitative comparison of the electrocutaneous display schemes of mobility information.

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