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Environment Sensing - A New Approach to the Design of an Electronic Aid for the Blind

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Abstract

Environment sensing is defined as the collecting of sufficient information in useable form concerning one's environment to permit safe mobility. Primary emphasis is placed upon the design of a device suitable for use by the blind. However, several other important applications await its completion. It is assumed that environment sensing should be accomplished with passive devices, that is, no transmitters or special light sources should be needed, and that the environment sensing device should produce no degradation of the sense of hearing. Two devices are described: One accepts light approaching over a very small solid angle; the other accepts light over a reasonably large but adjustable solid angle. The geometrical problems associated with the use of these sensors are discussed in some detail. Finally, environment sensing is described in terms of eleven simple problems suitable for a theoretical mechanical man (machine) to solve. A blind human being should be able to solve at least these eleven problems if provided with a suitable transducer for relaying the information to his brain. A transducer using the sense of touch is suggested as being most desirable. Both the sensing device and the transducer appear to be physically realizable with solid-state electronic circuitry.

Acknowledgments

The author is indebted to Dr. D. D. Foster, AFCRL, for information concerning Bessel's method of orienting a plane table in surveying and means of applying some mathematical developments to the problem of environment sensing; to Mr. B. L. Buchanan, AFCRL, for suggestions made in reviewing the manuscript; to Dr. John Coules, ESD, for information and numerous references concerning the physiological aspects of vision; and to Miss Olive N. L. Denniston, AFCRL, for numerous improvements made in the process of editing.

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Environment Sensing - A New Approach to the Design of an Electronic Aid for the Blind

1. INTRODUCTION

To those who have eyes, environment sensing is not a problem. To those who do not have eyes, it is an almost insurmountable problem. A precise definition of environment sensing as performed by those who have eyes is exceedingly difficult because complex functions of the brain are involved, and no one knows exactly how the brain works. A great simplification in the problem can be made by saying that the environment is "sensed" when sufficient information has been collected to permit an individual to move about safely. Safe mobility in various environments is an objective for certain types of unmanned vehicles as well as for the blind.

In designing any device, it is well to examine the characteristics of existing devices that perform similar or related functions. The eye-brain combination certainly provides an excellent example to follow - if we were only capable of duplicating it! Since the blind man usually has a very capable brain, we need only provide the proper eye-functions - still a formidable task! The camera may also be considered an environment sensor. It can produce an excellent reproduction of the environment it "sees," but the information in this reproduction is not readily available for the brain to use. The optics of the camera and the eye are similar, however, and can be duplicated easily. The bat senses his environment by emitting and collecting vibrations, both sonic and ultrasonic, in the atmosphere. He uses the sense of hearing instead of sight. Since radar and sonar, operating on the same principle as that used by the bat, have been perfected, many attempts have been made to construct radar- or sonar-like devices to aid the blind.[1] These devices have generally been coupled to the blind man's brain through his sense of hearing - a sense that is extremely important to him in its own right. The improvement in environment sensing provided by these devices has usually been offset by the degradation to the sense of hearing. A dog is capable of sensing his environment fairly well using only his sense of smell, but we know of no way to duplicate this capability.

A blind man can use his hands to feel near-by objects, and he can extend his reach with a cane. The use of a cane ordinarily involves the use of both the sense of touch and the sense of hearing. If we can find a way of extending the blind man's reach without using a cane,that is, a way of letting him determine the presence, shape, etc., of distant objects through his sense of touch, then perhaps he can learn to recognize objects at a distance and eventually be able to perambulate safely without difficulty.

2. APPROACH

If we consider environment sensing as a communications problem, a new approach to its solution becomes apparent. Figure 1 illustrates a typical communications system as described by Shannon,[2] with an additional block for storage of information and one to indicate action produced as a result of messages received.

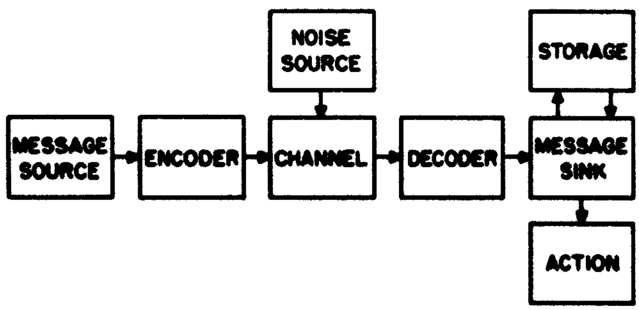

Figure 1. Typical Communication System

We may consider the signals coming from an environment sensor as being an encoded message describing the environment. Since the description will probably not be entirely accurate, each message will correspond to a more accurate message that has been garbled by the addition of a certain amount of "noise." These noisy messages describing the environment must somehow be "channeled" into the brain, which of course is the "message sink." The brain certainly possesses adequate storage for comparison of one message with another, and for recognizing well-defined characteristics of particular messages. It would seem that almost any type of environment sensor could be used, as long as it actually produced recognizable messages which could be put into correspondence with the environment.

Observation of the manner in which children develop a capability to judge distance and estimate the size of objects indicates that there is a considerable amount of "learning" involved in the use of our eyes to sense our environment. Apparently, learning can take place by comparing the new or unfamiliar with the known. This indicates that our artificial environment sensor must not only provide a recognizable message for known objects, but it must also be able to indicate relationships between various objects.

Studies of the optics of the eyes usually do not involve the system of muscles which control eye motions and the muscles of the neck which control the position of the head. Certainly, the brain is aware, either consciously or unconsciously, of the action of these muscles and learns to interpret visual signals with respect to the corresponding muscular action or position, or both. Gibson[3] gives consideration to factors other than the physical optics involved. His interpretation of the "Visual World" indicates the importance of the background in identifying objects, and in fact, in all environment perception. If environment sensing information could be channeled to a blind man's brain through the skin on his face, then it would be possible to attach the sensor to his head so that he could focus it on any object he wished; this focusing would be done in much the same manner that people with eyes look at anything they choose. Or, if the sense elements on the fingers were chosen, then he would be able to "feel" objects at a distance. Ideally, a sensor coupled to the head would be more suitable, because then it would permit the muscles which control the position of the head to be used in the same way that a person who can see uses them. The hands would then be left free.

The eye is a sensor which makes use of light rays that come to it naturally. It thus senses the environment without transmitting energy in the manner of bats and radar or sonar devices. If we wish to emulate the eye insofar as possible, then we should design a passive sensor; that is, it should not radiate energy in any form. Figure 2 illustrates in block diagram form the nature of our problem. The light source may be the sun or any other external light. The sensor is required to process this reflected light so that messages describing it will be fed through the transducer into the human brain. In keeping with our definition of environment sensing, the brain is then required to ask for movements in the environment. If the process is accomplished correctly, the movements will avoid collisions, pitfalls, etc. Figure 3 illustrates the same environment sensing problem in a more objective manner. Here, a computer is asked to program safe movements on the basis of information received. The transducer problem is thus avoided.

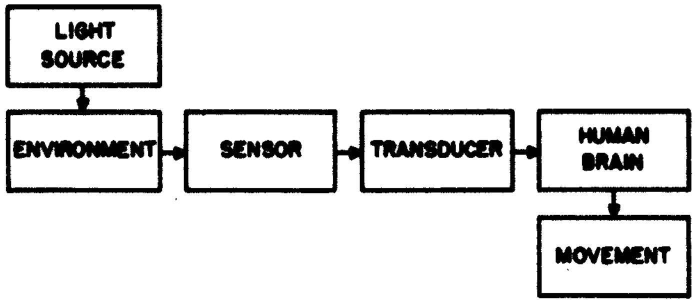

Figure 2. Information Flow for Environment Sensing

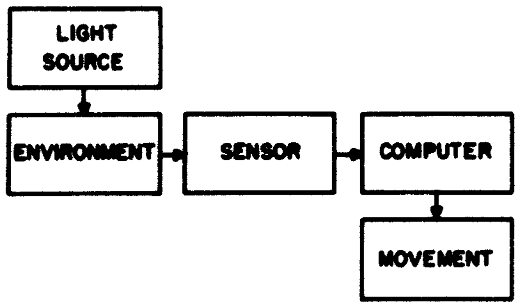

Figure 3. Objective Environment Sensing Problem

The transducer which carries the environmental information from the sensor to the central nervous system, and thence to the brain, is limited both by the number of sense receptors available and by the frequencies to which they are capable of responding. The fact that the number of receptors per square centimeter is greater on the fingertips than in other areas, indicates that at least for experimental studies, artificial sensors should be coupled to the brain through the fingertips. However, until more is known about the actual information capacity required, the use of receptors on the skin of the face near the eyes should not be ruled out. A crude transducer consisting only of a vibrating "whisker" which could touch a number of receptors as it vibrates, might be capable of carrying the information required. At least one investigation of the response from electrical current applied to the skin about the eye has been made.[4] Further experimentation will be necessary, however, in order to determine the frequency discrimination capability of the skin with various feasible transducers. The feasibility of using direct electrical inputs for environmental information is also in need of further experimentation.

Regardless of the method of coupling used, it is unlikely that the quantity of information carried over the optic nerve could ever be carried over an artificial transducer. However, environment sensing need not be as complete as that provided by the eyes in order to be of considerable value. Further, when we speak of safe mobility, we do not at the outset ask for <u>rapid</u> safe mobility. In other words, a first approach would permit the blind person to take plenty of time in sensing his environment. The process should be considered a success if it is <u>accurate</u> even though somewhat slow and admittedly incomplete. In analogy, the hands take a considerable amount of time in sensing the shape of objects which the eyes can sense at a glance. Nevertheless, given enough time the hands can determine the shape accurately.

To summarize our approach to the design of an electronic aid for the blind: we wish to process natural light in such a manner that its effect will be "felt" by selected portions of a blind man's skin, perhaps on his fingertips, but preferably on this face (ideally on the skin under an ordinary pair of eyeglasses). We shall use a mechanical man (machine) to illustrate the problems to be solved by the brain when a proper transducer is provided.

3. SENSING DEVICES

Before transistors and solid state electronic circuitry were available, it was accidentally discovered during some laboratory experiments that natural reflected light passing through two pinholes would produce some very interesting outputs from a photomultiplier.* When the output of the photomultiplier was amplified and connected to a pair of earphones, it was possible to detect variations in the texture of objects in the field of view. The electronic equipment required to provide the desired output was too bulky to permit exploitation of the phenomenon at the time. Also, a brief investigation of other efforts to aid the blind by using the sense of hearing indicated that any such device would be doomed to failure. More recent studies of the nervous system[5,6] have led the author to the conclusion that information concerning the texture, etc., of distant objects can be channeled to the brain through the sense of touch. The signals which reach the brain through such channels will be trains of pulses, as all nerve signals are. If each set of such signals represents a particular characteristic in the environment, the brain should be able to learn the correspondences. We may thus leave the complex decoding to the brain and concentrate on obtaining a device which will produce different sets of signals (messages) as it views different portions of the environment.

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*Research recorded in AFCRL Communications Laboratory Notebook No. 55, September 1947.

Figure 4 illustrates a highly directional optical sensor. The two small apertures, O and F, restrict the light which can reach the light sensitive cell C. If the aperture O is of proper size, it will focus the image of all objects in the field of view onto the plane of the second aperture F in the same manner as the aperture of a pinhole camera focuses an image on the film. In keeping with the Fresnel theory of diffraction,[7] the aperture O should subtend approximately nine-tenths of a Fresnel zone as measured at the plane of F. The size of the aperture F is not so easy to determine. Aperture O will act as a somewhat crude point source for aperture F, and hence the light passing through F will be subject to further diffraction. It is relatively easy to make the photocell C large enough to encompass all light which passes through F; so the size of aperture F must be determined by other considerations. For an exceedingly narrow-beam directional sensor, it would seem that aperture F should be the same size as aperture O. Further experimentations is needed in order to determine the best size for producing recognizable outputs when the sensor scans various textures. Actually, as it will be shown later, it is not the relatively constant output that comes from viewing any particular surface that is most useable; rather, it is the more pronounced change in response produced when the sensor's field of view passes from one object to another, or past a sharp corner or edge of an object.

The schematic drawing of an amplifier A and a battery in Figure 4 is included only to indicate that all should be in the same physical unit. With solid-state circuitry, a photosensitive cell, an amplifier, and a source of power should be exceedingly small. Also, the transducer to which the output would have to be coupled should be tiny.

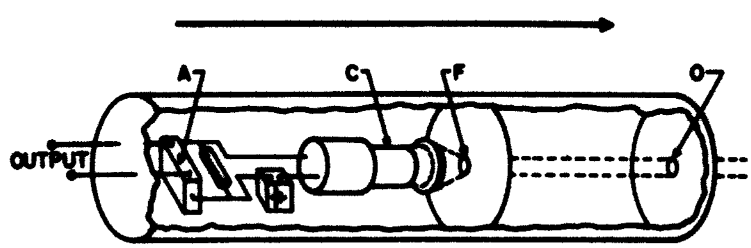


Figure 4. Highly-directional Optical Sensor.

Figure 5 shows a sensor which will accept a larger solid angle of light. Of course, the same wider angle can be produced by enlarging aperture F instead of O. And, reducing the distance between O and F will also increase the angle of observation. If aperture O, aperture F, or the distance between O and F can be made adjustable, sensing capabilities will be considerably increased. Even without adjustment, this wide-angle directional sensor should be helpful in locating objects that cannot be found easily with the more directional sensor. The electronic circuitry for the wide-angle sensor is essentially the same as that for the more directional one. However, some distinguishing features may be needed in the transducers provided for them. Amplitude and frequency of vibration and position on the skin are parameters readily available for variation in a transducer operating on the sense of touch.

If the sensor shown in Figure 4 is capable of "recognizing" various textures, the edges of objects, etc., then it has roughly the capabilities of a very small group of rods on the retina. Thus, the capabilities of the sensor do not represent much true "vision." However, if the sensor can be placed in prescribed positions and oriented properly in the environment, a considerable amount of environment-sensing information can be collected. The arrow shown in Figure 4 is used in some of the succeeding figures to indicate the position and orientation of the sensor as it gathers information.

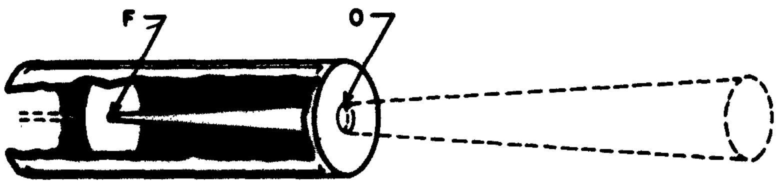


Figure 5. Wide-angle Directional Sensor.

4. GEOMETRICAL CONSIDERATIONS

The manner in which the two types of sensors can collect information about the environment surrounding them requires a number of separate considerations. This portion of the problem is broken into the two major parts: Height Sensing and Distance Sensing.

4.1 Height Sensing

If we locate the directional sensor of Figure 4 a known distance h_s above a plane surface and allow the sensor to rotate about the point F in a vertical plane, then there are two simple means of sensing the height of objects which appear in the sensor's field of view. Figure 6 illustrates height sensing when distance is known. In this figure:

$$h_A = h_s - a \tan |\alpha| \quad (1)$$

$$h_B = h_s \quad (2)$$

$$h_C = h_s + c \tan |\beta| \quad (3)$$

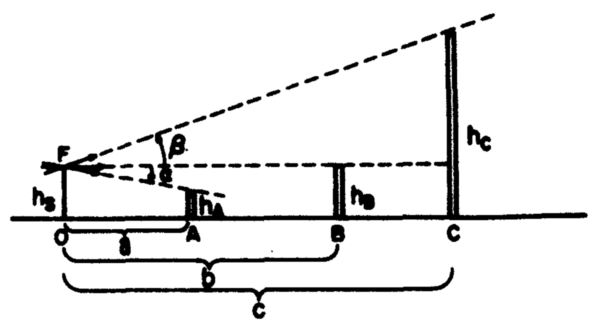


Figure 6. Height Sensing When Distance is Known.

Figure 7 shows a method of determining height by comparison with an object of known height (in this case one of height h_s). Here

$$h_A = h_s \left[1 - \left(\frac{\tan |\alpha_u|}{\tan |\alpha_b|}\right)\right] \quad (4)$$

$$h_B = h_s$$

$$h_C = h_s \left[1 + \left(\frac{(n-1) \tan \beta_u}{\tan \beta_n}\right)\right] \quad (5)$$

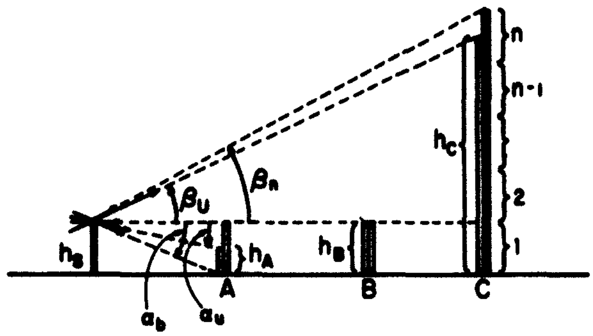


Figure 7. Height Sensing by Comparison with an Object of Known Height.

where

n = number of standard objects, placed one on top of another at the distance of the unknown object, required to reach a height greater than that of the unknown object.

Either of these trigonometric expressions can easily be evaluated by a computer. However, it is more likely that human beings use a comparative method instead of evaluating these expressions. The examples given serve only to illustrate some of the techniques that can be used in sensing the environment.

Gibson's[3] statement, "The spatial character of the visual world is given not by the objects in it but by the background of the objects," leads us to a set of comparisons which makes use of the background as a scale for determining height-distance information.

Figure 8 shows a scale at a known distance D as the background for an observed object. The sensor at F tells us the height of the observed object if its distance from O or D is known. Or, it tells us these distances if the object's height is known, since the similar triangles imply that

$$\frac{h_b - h_s}{h_u - h_s} = \frac{d}{b} \quad (6)$$

This relationship can be used repeatedly to establish the height or distance of many objects. The fact that each new object measured becomes a new and better scale for all nearer objects (and a useable scale for the more distant if extrapolation is used) soon leads to a rather complete calibration of all objects in the

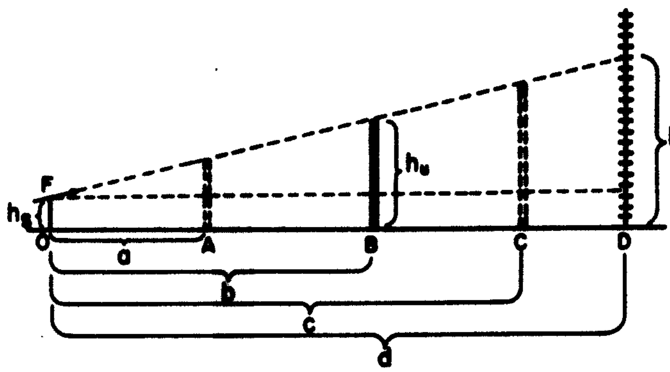


Figure 8. Use of a Background Scale.

field of view. Although here we have considered only a single vertical plane passing through F, it is not difficult to visualise comparing the height of objects in one such plane with that of objects in another vertical plane passing through F. The sensor of Figure 4 can make such comparisons easily, since the angles of observations can be marked on the scale of a rotatable protractor. Rotation of the sensor about F in a horizontal plane does not change the problem of measuring height, or distance from the sensor.

A large number of observations of the type previously described taken from a single point could be used by an electronic computer to calibrate the environment of the sensor in cylindrical coordinates (see Figure 9). The angle ϕ is of no consequence in the actual height measurement except to indicate that any number of vertical planes passing through F may be considered. This angle is important, however, in establishing the orientation of objects with respect to the sensor. The distance r from the sensor F to any object may be found from the equation

$$r = \rho \sin \theta \tag{7}$$

and the height h of any object is

$$h = \rho \cos \theta \tag{8}$$

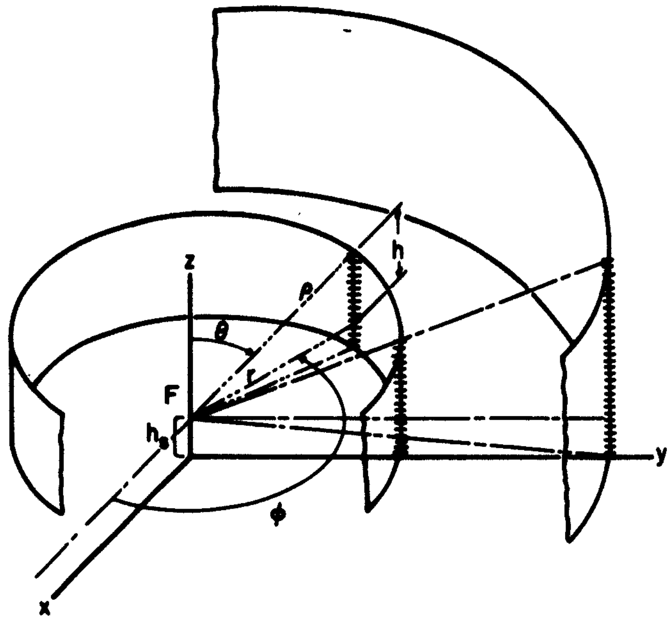


Figure 9. Height-distance Data in Cylindrical Coordinates.

The transformation from observations of the type shown in earlier figures to the cylindrical coordinates of Figure 9 is the conventional one:

$$\left.\begin{aligned} x &= \rho \sin\theta \cos\phi \\ y &= \rho \sin\theta \sin\phi \\ z &= \rho \cos\theta \end{aligned}\right\} \qquad (9)$$

where for each observation to determine x, $\phi = 0$, and for each observation to determine y, $\phi = \frac{\pi}{2}$.

Even with this completely calibrated environment, the exact height and distance of a new object placed at random cannot be computed. If its height or its distance could be determined by some other means, however, then the other would be immediately available.

4.2 Distance Sensing

The directional sensor of Figure 4 can be used for distance sensing by means of selected observations taken as the sensor rotates in a horizontal plane. But this method involves comparison with some known standard distances or a series of "sightings" similar to those taken in establishing the position of a ship. If a known distance scale is located in a suitable position with respect to an object whose distance is unknown, it is possible to determine distances by the means illustrated in Figure 8. We simply consider a horizontal plane instead of a vertical one. This procedure is very unrealistic, however, since such suitably-placed distance scales are seldom found in nature.

Figure 10 illustrates a method of establishing a vessel's position when three known landmarks A, B, C are visible. Voorhis[8] describes the use of this method in great detail. Briefly, it involves measuring the angles α and β from the ship's position O (or that of our directional sensor) and then adjusting a three-armed protractor so that the lines d_A, d_B, and d_C pass through points A, B, C, respectively, on a chart where the points are known, while the angles α and β remain fixed. Voorhis also describes Bessel's method (which is a great deal simpler) of orienting a plane table in surveying, or establishing a vessel's position, by using

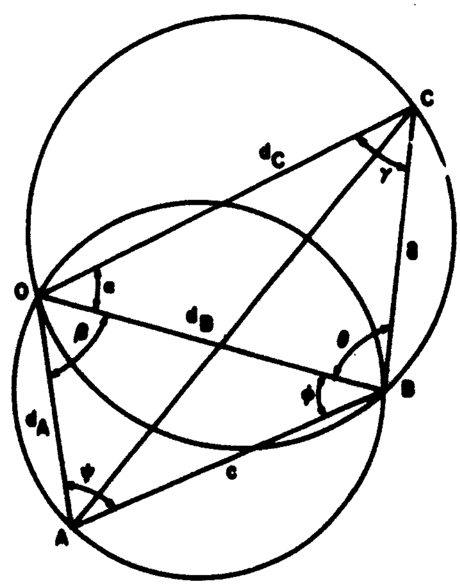


Figure 10. Distance Measurement Using Three Known Points.

the auxiliary lines shown in Figure 11. Here, the position O is found by simply drawing two lines from points A and B so that the angles α and β are formed as shown in the figure. If a line is then drawn through the intersection of these two lines (point E) and the point B, its extension will pass through the vessel's position O. Finally, a line is drawn from C such that it makes an angle ϕ with respect to line CA, ϕ being determined by lines AE and EB. (The other angle CEB may be used at point A just as well.) This line will intersect the extension of EB at the vessel's position O. Thus, we see that the position is established by using a simple protractor and straight edge, and only four lines need be drawn. If we wish to avoid graphical methods to establish the sensor's position, O, we may program our computer to solve the following equations for the distances d_A, d_B, d_C in Figure 10 from the sensor to the three points:

$$a^2 = d_A^2 + d_B^2 - 2d_Ad_B \cos \alpha \tag{10}$$

$$c^2 = d_B^2 + d_C^2 - 2d_Bd_C \cos \beta \tag{11}$$

$$b^2 = d_A^2 + d_C^2 - 2d_Ad_C \cos (\alpha + \beta) \tag{12}$$

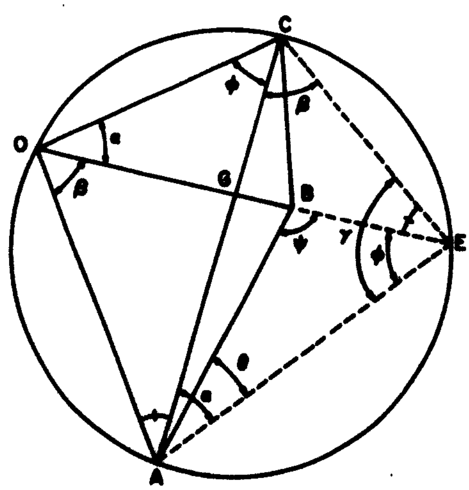


Figure 11. Auxiliary Lines Used in Bessel's Method of Orienting a Plane Table.

where

a = BC

b = AC

c = AB

These equations may be replaced by others derived using the auxiliary lines shown in Figure 11. Besides describing both of these methods of determining position, Voorhis[8] provides convenient transformations to Cartesian and polar coordinates and a representation in bipolar coordinates.

Figure 12 shows a particular case of great importance to environment sensing in the civilized world. The three points A, B, C in this figure represent the three corners of a room, or one corner and objects against the intersecting walls. The three points A, B', C represent the outside corners of a building. The mathematics involved in computing the desired distances is somewhat simpler for this case. The ambiguity resulting from the fact that B and B' appear at the same angle cannot be removed by observance of angles. Other cues must be used by the observer or the computer in selecting the correct answer. Of course, a human being usually has no trouble determining whether he is sensing the "inside of a room" or the "outside of a building." The use of such points in distance measurement is so commonplace that we do not always remember that the entire process had to be "learned." And since it has been learned, it provides a very convenient means of producing illusions, especially in the motion picture industry. We customarily measure the size of objects and distances on a screen by comparing them mentally with things we have seen. A photograph of an accurate miniature model cannot be distinguished from a photograph of the real object.

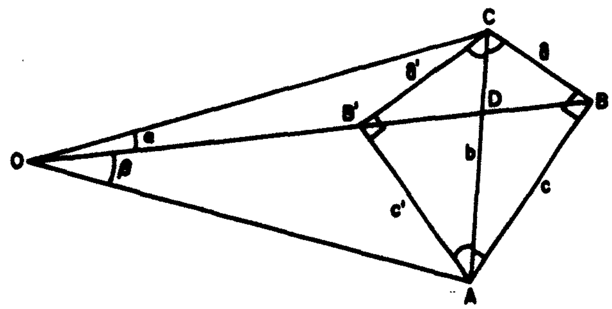


Figure 12. Most Important Particular Case.

The procedure of measuring distance by means of trigonometry is perfectly acceptable for a computer. But people, and all other kinds of living creatures, learn to judge distance with a reasonable degree of accuracy without resorting to such means.

The wide-angle directional sensor of Figure 5 provides an entirely different means of measuring distances. Suppose, for example, that this wide-angle sensor is placed successively in the series of positions shown in Figure 13, and assume that the distance to one object A in the field of view is known. If the series of positions is in a straight line as shown, objects nearer than A, such as B and D, will appear in the field of view from a smaller number of positions, and objects such as C farther away than A will appear from a larger number of positions. (The asterisks indicate the number of objects in the field of view at each position.) Such simple distance comparisons might easily be made by a chicken's eye, as the chicken walks in a straight line. It should perhaps be noted here that motion of any of the points in the field of vision could very easily cause false interpretations of distance. For example, if point C should move rapidly to position C' immediately after being viewed for the first time, it would appear to be the same distance away as point A. (It would remain in view from the same number of positions.) Such confusion might help explain why a chicken is easily startled by rapid motion even at a distance.

Since observation at a series of points is not always convenient (especially if it is wished to sense environment with a computer) an alternate simple means of measuring distance is desirable. The same effect can be obtained, and a finer degree of measurement achieved, if the wide angle directional sensor is allowed to

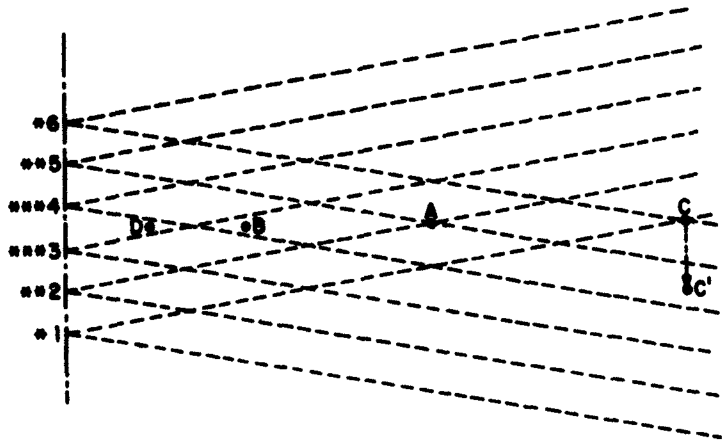


Figure 13. Simple Distance Comparison.

assume only two positions but its angle of observation is made adjustable. Figure 14 shows measurements being made to the object A-D of Figure 13 by this means. (The four pairs of observations are drawn separately for clarity.) Here, distance d varies inversely with the tangent of half the angle of observation α, since

$$d = \frac{K}{2 \tan \frac{\alpha}{2}} \tag{13}$$

where

K = distance between observation positions 1 and 2.

Of course, the direction sensor of Figure 4 could also be used for the measurements illustrated in Figure 14, but location of the objects would be somewhat more difficult. Figure 15 illustrates this type of measurement.

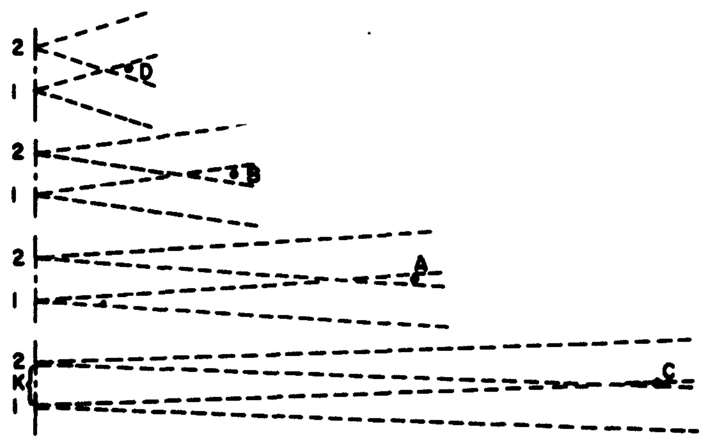


Figure 14. Distance Measurement by Adjustable Wide-angle Sensors.

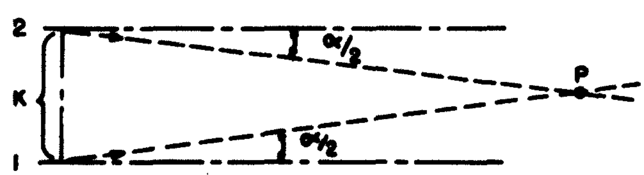


Figure 15. Distance Measurement Using Narrowbeam Directional Sensor.

If we allow simultaneous use of the two types of sensors and locate them as shown in Figure 16, then the wide-angle sensor can measure distances while the narrow-beam sensor measures height. Both kinds of information can then be delivered to a properly-designed computer which should be able to determine a reasonable facsimile of its environment.

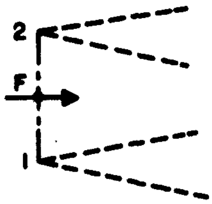


Figure 16. Locations for Simultaneous Use of Both Types of Sensors.

If these two types of sensors can be made suitably compact and coupled to moving parts of the human anatomy, as suggested earlier, then the changes in outputs would automatically be correlated with directions. At least in theory, they should provide a set of signals which could be interpreted as the environment, since there would be a one-to-one correspondence between them and the environment.

5. SPECIFIC ENVIRONMENT-SENSING PROBLEMS

Since environment sensing involves so many parameters, various parts have been selected to be considered as separate problems. Also, since the construction of a transducer for use by human beings is a difficult problem in itself, consideration of its design will be made separately. If we assume that environment sensing is going to be performed by a mechanical man endowed with the capability of producing movements in accordance with information received from environment sensing devices, we can avoid, temporarily, all transducer problems. Eleven relatively simple, but important, environment sensing problems have been selected for our mechanical man, whom we shall christen "Edgar," to solve. We assume now that directional and wide-angle sensors are attached to Edgar's head so that he can "look" in any direction.

5.1 Problem 1: Obstacle Avoidance (Figure 17a)

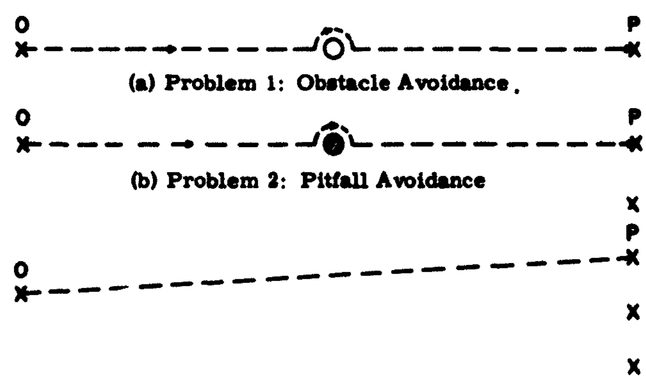
The directional sensor of Figure 4 should enable Edgar to determine in which direction obstacles are located and in which direction there are none. Edgar merely has to rotate his head in order to scan the area in front of him. The sensor is required only to distinguish the difference between essentially free space (only distant objects present) and light reflected from a near-by object.

5.2 Problem 2: Pitfall Avoidance (Figure 17b)

If Edgar nods his head and moves it up again, his directional sensor should tell him whether the ground in front of him is level or rough, and should indicate clearly such things as the sharp edges surrounding a hole. (Motion of the sensor past these edges will produce a major change in the response from the sensor's photocell.) The nature of the difference between a smooth and a rough surface is not important. The sensor is required only to indicate a distinguishable difference; that is, one which is recognizable.

5.3 Problem 3: Recognition of Objectives (Figure 17c)

Edgar may find it necessary to scan his environment several times in order to recognize the response his sensor gives as representing a particular object. A post of known height and shape, such as a public mailbox for instance, could be recognized by several horizontal scannings at different levels. The difference between people and fixed objects such as trees or buildings should be considerably simpler to recognize. To distinguish one person from another, however, would probably not be possible unless they differed considerably in size, or wore clothes having distinguishing characteristics.



(a) Problem 1: Obstacle Avoidance.

(b) Problem 2: Pitfall Avoidance

(c) Problem 3: Recognition of Objectives

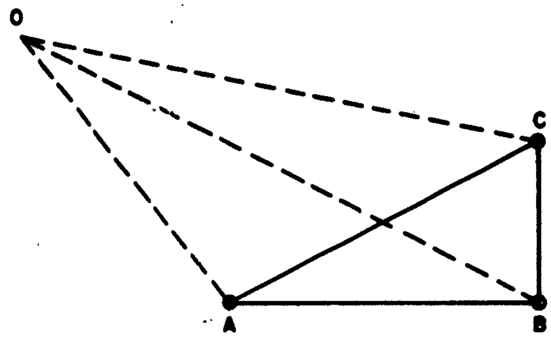
Figure 17. The Simplest Environment Sensing Problems.

5.4 Problem 4: Bearings from Three Known Points (Figure 18a)

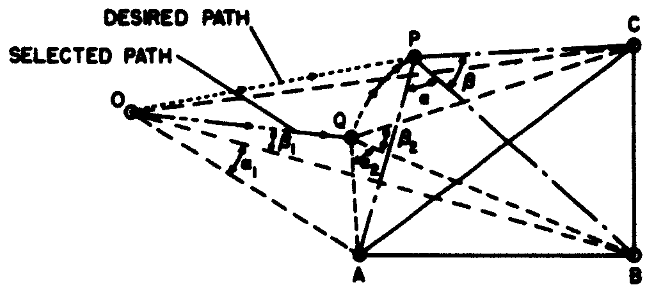
This problem is identical to that of establishing a ship's position with respect to three known points. Edgar should be able to measure the angles AOB and BOC by using his directional sensor. If he can establish the distance OA, OB, or OC by some other means - for example, by triangulation or by using his wide-angle sensor - he can avoid the complexities of trigonometry or the plotting board. It is not difficult to find examples where Edgar would know the height of an object at one of the points A, B, C and hence could easily determine its distance from O.

5.5 Problem 5: Navigation to a Position Having Specified Bearings from Three Known Points (Figure 18b)

Edgar might experience considerable difficulty in going straight to a position having specified bearings from points A, B, C in Figure 18b. It would not be difficult, however, for him to reach the desired destination by concentrating on one angle at a time. Suppose, for example, that he notes that the angle AOB (α_1 in Figure 18b) is less than the desired angle α measured at the point P to which he wishes to navigate. He may ignore the other angle, β_1, momentarily and move in any direction which increases the measured angle AOB. In Figure 18b his selected path makes angle AOB equal to α at point Q. Here, the angle BOC (labeled β_2 in the figure) is smaller than the desired angle β. From point Q, he can follow the locus of points where angle AOB remains constant until his measured angle BOC is equal to the desired angle β. A human being in Edgar's place should not find it too difficult, after some practice, to follow a reasonably straight path to his objective by using similar techniques. The fact that there are two positions having the same angles α and β could confuse Edgar unless he makes some distance measurements to determine the relationships between the distances OB and OA or OC. $OB < OA$ and $OB < OC$ would indicate that he is on the opposite side of the triangle from that shown in Figure 18b. It is unlikely that a human being would be bothered by this ambiguity, however, because the points used most often would be the outside corners of a building or the inside corners of a room, or some similar set of familiar points. (There are of course certain choices of angles which can be satisfied by a number of positions. The technique described fails for these angles.) The two problems shown in Figure 18 are considered to be difficult environment sensing problems because they involve simultaneous (or almost simultaneous) consideration of several sets of messages from the sensors.



(a) Problem 4: Bearings from Three Known Points.



(b) Problem 5: Navigation to Position Having Specified Bearings from Three Known Points

Figure 18. Difficult Environment Sensing Problems.

5.6 Problem 6: Step Down (Figure 19a)

This problem is similar to problem 2 as far as determining where the edge of the step is located. It would be convenient if this sensor could detect a difference between the texture of the plane surface at the bottom of the step and that of the surface at the top. If the textures are the same, Edgar must resort to the use of associated information (such as the knowledge that he is approaching a well-known street, for instance) to determine the depth of the step. In the absence of such information, Edgar must step down slowly and essentially "feel his way." If the sensor were attached to Edgar's fingertips, he would be able to measure the depth of the step more accurately before stepping down. However, it is doubtful if he would care to stand at the edge of the step and move his hands to the necessary positions.

5.7 Problem 7: Step Up (Figure 19b)

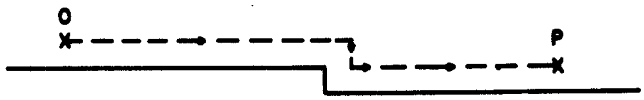
Edgar should experience no difficulty either in locating the position of the "step-up" or measuring its height. He would only have to nod his head to obtain two sharp indications marking the top and bottom of the step. He could, however, forget to nod his head often enough and overlook a step that he was approaching. The wide-angle sensor of Figure 5 should help provide a warning of hazards such as this which might be missed by the more directional sensor.

5.8 Problem 8: Low Bridge (Figure 19c)

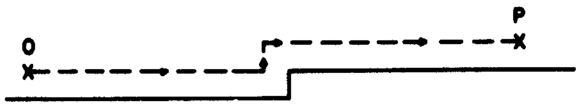
The presence of a "low bridge" would be detected first in the same manner as the presence of any other obstacle (problem 1). Its presence would be missed, however, if Edgar kept his head tilted downward, or if he had an angle of observation too small for the low bridge to be detected. (People who can see sometimes bump their heads for the same reasons.) For utmost safety then, Edgar must scan his environment both above and below that covered when his sensor is in a horizontal position. Except for the obvious mechanical problem (which we neglect) of stooping to avoid the obstacle, the low-bridge problem is not difficult. The lower edge of the obstacle should be very easy to detect in the same manner that the top edge of the "step-up" can be detected (problem 7).

5.9 Problem 9: Exit from Low Bridge (Figure 19d)

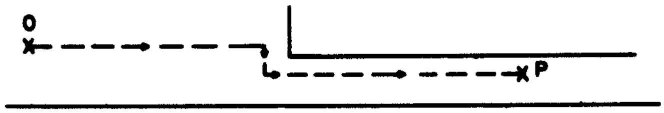
After stooping to avoid hitting the low bridge, Edgar must "look up" to determine when it is safe to stand erect again. This problem is very similar to the step-down problem, but here he is not concerned if there is nothing beyond the "step;" that is, he needs to measure the height of this "step-up" only if he is worried about a variable height bridge in which he could still bump his head. In most practical instances, a blind man would be concerned only with such problems as ducking under a tree branch or a low doorway. Thus, problems 8 and 9 would be combined into one very simple problem.



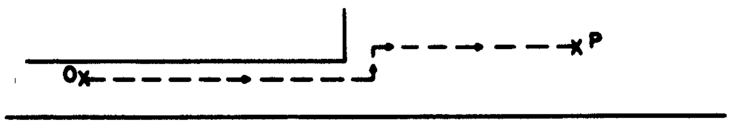
(a) Problem 6: Step Down



(b) Problem 7: Step Up



(c) Problem 8: Low Bridge



(d) Problem 9: Exit from Low Bridge

Figure 19. Environment Sensing Problems Involving the Vertical Plane

5.10 Problem 10: Recognition of Approaching Vehicle (Figure 20a)

The vibrating surface of a moving vehicle will cause Edgar's sensors to indicate a different "texture" from that present when the vehicles are not moving. This texture alone will not always be recognizable as indicating motion, but it should aid Edgar in keeping his sensor focused on the object in question. Edgar needs to stand still for only an instant to determine how the relative position of an object is changing. If he is concerned about approaching vehicles as he is about to cross the street, the position of the vehicle on the street will also help. He should not assume categorically, however, that all vehicles will be traveling where they should. (Many people who can see are killed by making this assumption.)

5.11 Problem 11: Recognition of Departing Vehicle (Figure 20b)

A departing vehicle and an approaching vehicle will indicate essentially the same "texture" to Edgar's sensors. If he follows the vehicles with the sensor, however, he can soon eliminate from consideration those vehicles which are leaving and thus concentrate on those which constitute danger.

(a) Problem 10: Recognition of Approaching Vehicle

(b) Problem 11: Recognition of Departing Vehicle

Figure 20. Recognition of Moving Objects.

5.12 Typical Environment Sensing Situation

Figure 21 illustrates an environment in which all eleven of the enumerated problems are encountered. Edgar is asked to travel from his present position O to the door of his house P. During this travel, he must perform the following:

a. He must duck under the tree limb and return to his normal stance (problems 8 and 9 respectively).

b. He must avoid the open manhole (problem 2).

c. He must recognize the familiar street lamp and mailbox (problem 3) in order to determine where to cross the street. (He might also locate the lines marked on the street).

d. He must determine when it is safe to cross the street (problems 10 and 11).

e. He must step down onto the street (problem 6) and up onto the sidewalk on the other side (problem 7).

f. He must avoid the small lamp post in his path (problem 1).

g. He must recognize the three corners (labeled A, B, C) of his house (problem 3 again).

h. He must navigate to the center of the side wall of the house where he knows that a door is located. (We assume that the door is not readily recognizable from a distance.) He may use point D or E as an aid when he can no longer see point A.

Many of these problems will, of course, be encountered again inside the house if he is to have freedom of motion without touching objects with his "hands."

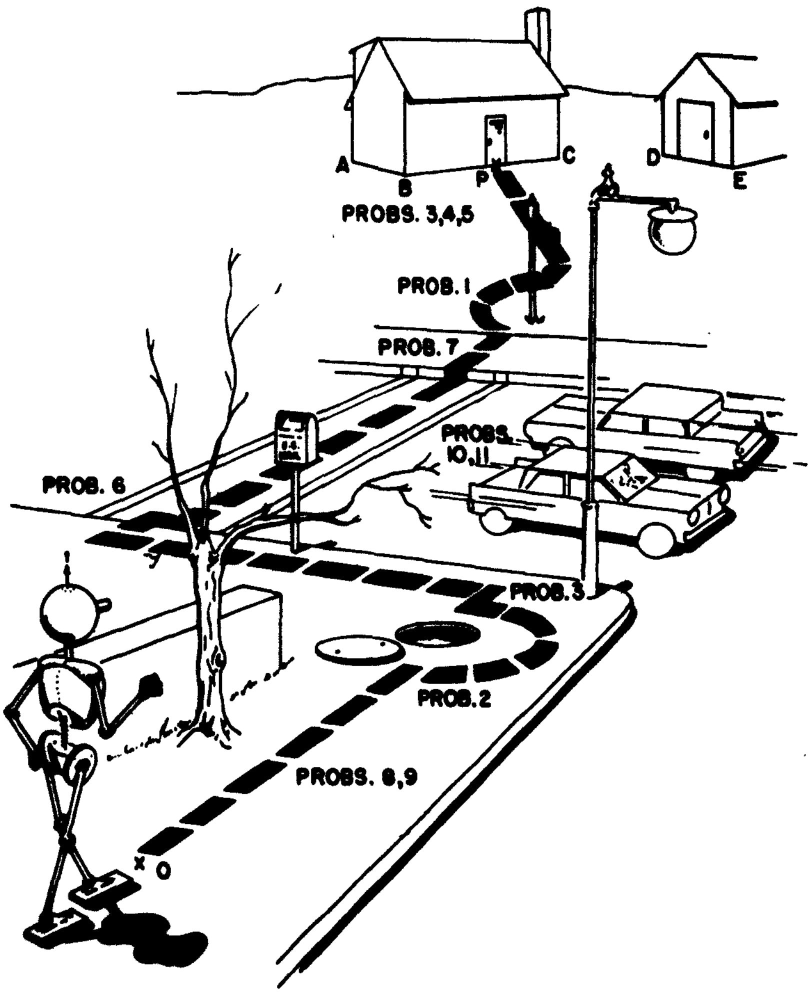


Figure 21. Environment Involving All Eleven Typical Problems

6. THE TRANSDUCER

A transducer of the type shown in Figure 22 is considered more likely to be suitable for environment sensing information than one which uses the sense of hearing. The oscillator may be either of fixed frequency or one in which the frequency varies with the input; that is, it may be either amplitude-modulated or frequency-modulated, or perhaps both. In any case, the oscillator's output is

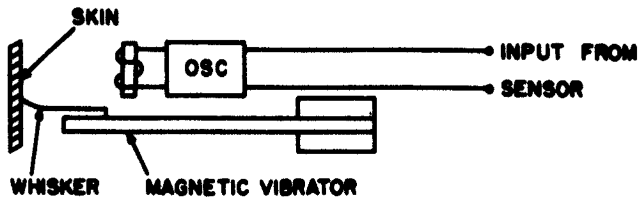


Figure 22. A Mechanical Transducer

controlled by the input from an amplifier (part of the sensor shown in Figure 4), which in turn is controlled by the response of the light-sensitive cell C. Since a mechanical vibrator has a relatively sharp resonant frequency, this type of transducer will be most effective if the sense receptors also have a maximum response to some particular frequency. If they show no particularly sharp maximum response frequency, the transducer will still be effective if the frequencies which produce a minimum response from the sense receptors are avoided.

If a direct electrical input can be used, then the mechanical vibrator may be eliminated with a resultant reduction in size of the transducer. Such a transducer is shown in Figure 23.

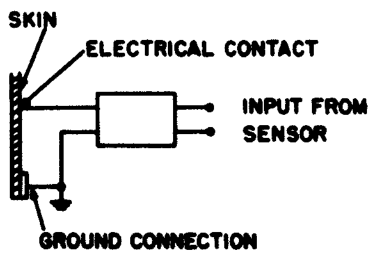


Figure 23. An Electrical Transducer

If solid-state electronic circuitry is used for these transducers, they should be small enough to be attached to an ordinary pair of eyeglasses. Even without careful engineering, they should be of such a size as to be carried easily in the hand. In both cases the power supply should be self-contained.

Further study of the transducer problem is needed both from the electronic and physiological point of view. The theoretical descriptions of environment sensing could also be tested by using the sense of hearing, but a truly practical finished product should not be expected from such investigations.

7. CONCLUSIONS

The arguments set forth have convinced the author that a completely passive environment sensor can be built. Its design should be based upon data received from one or more highly-directional light sensors and one wide-angle sensor. The transducers for coupling information from the sensors to the brain require further study and experimentation. However, since coupling through the sense of hearing could be used, the use of the sense of touch constitutes a refinement aimed at making the sensor practical for use by the blind, who need their hearing for other purposes. Passive environment sensors designed for use by the blind could also be used for guidance of various types of vehicles in environments where no human beings are available.

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March 1963. AFCRL-63-64 Unclassified report

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