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Optical Proximity Sensors for Manipulators

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PREFACE

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ABSTRACT

A breadboard optical proximity sensor intended for application to remotely operated manipulators has been constructed and evaluated in the laboratory. The sensing head was 20 mm x 15 mm x 10 mm in size, and could be made considerably smaller. Several such devices could be conveniently mounted on a manipulator hand, for example, to align the hand with an object. Type I and Type II optical configurations are discussed, Type I having a sharply defined sensitive volume, Type II an extended one. The sensitive volume can be placed at any distance between 1 cm and approximately 1 m by choice of a replaceable prism. The Type I lateral resolution was 0.5 mm on one axis and 5 mm perpendicular to it for a unit focused at 7.5 cm. The corresponding resolution in the axial direction was 2.4 cm, but improvement to 0.5 cm is possible. The effect of surface reflectivity is discussed and possible modes of application are suggested.

Introduction

Manipulator systems, or teleoperators, have been used for many years to do useful work in remote or hostile environments such as nuclear "hot cells," underwater, and in space. Useful reviews of this field with extensive bibliographies have been given by Deutsch and Heer [1] and by Johnsen and Corliss[2]. Although it is possible to approach the dexterity of a human in doing complex manipulations, a characteristic of such operations is that they are extremely slow. One of the reasons is that satisfactory machine substitutes for the sense of touch do not as yet exist.

Some previous work has involved sensing during the critical grasping phase of a manipulation. Bliss, [3] and his co-workers conducted experiments in which tactile sensor outputs were used to stimulate the operator's fingertips. Others [4, 5] have also discussed the subject of tactile sensing in this context. However, the possibilities of a noncontact or proximity sensor have not been explored.

The purpose of this paper is to describe an optical proximity sensor with potential for local control of a manipulator at the point of grasping. The device produces an output signal whenever a diffusely reflecting surface enters a sensitive volume having a fixed location with respect to the sensor. The magnitude of the output depends approximately on the position of the surface. The sensing head itself can easily be built small enough that several could be placed on a manipulator hand (effector).

The task which the present work addresses is that of sensing the position of either the effector as a whole, or that of the finger components individually with respect to an object which is to be grasped. The object is assumed to be irregular and optically a diffuse reflector. Sensors would be placed such that their sensitive volume is located near the "fingertips" of the manipulator. Information from the sensors would then be used to alter the position of the fingers and the orientation of the hand in order to facilitate grasping. In a sense, a proximity sensor can thus provide a limited sense of touch although actual contact does not occur.

We feel that it will be desirable ultimately to devise ways of using the proximity sensor outputs in local control loops, leaving the basic relationship between operator and manipulator unaffected. The term reflexive control is useful to describe this concept, as its connotation is accurate. Ferrell and Sheridan, [6] in their paper on supervisory control, described very similar ideas, but reflexive control would involve only the most rudimentary elements of supervisory control. Similarly, others have suggested local control loops[7] for manipulation and reflexive response [8] in autonomous machines. Reflex control inputs are visualized as supplements to the basic control loop involving the operator and manipulator. The operator would command the motions of the manipulator just as if the reflexive loop was not there. Sensor inputs would override or modify the operator inputs at critical points in such a way that his attention is not diverted from his visual display. The application of proximity sensing devices to manipulator control will be described in a future publication[9].

The remainder of this paper deals with the sensor itself and will give some examples of its output as a function of the position of a test surface. The final section discusses the potential and limitations of the present device.

Description of Device

The sensor concept may be visualized with the aid of Fig. 1. An illuminator and compatible detector are provided in a suitable housing, each with its own focusing lens, such that the optic axes of the two converge at a focal point. The presence of an object is detected when light is diffusely reflected back towards the detector. A fixed optical geometry defines a sensitive volume from which a return can be received, basically by triangulation. Such a configuration will detect the presence of a surface near the focal point, but if the surface is either closer or further away, no return will be detectable. The distance from sensor to the focal point, the focal distance, can be set by adjusting the convergence angle of the illuminator and detector axes. A similar triangulation principle has been used in other devices to sense position, but the earlier sensors were much larger and were intended for other purposes. [8, 10]

In practice, if the light source area and detector field of view are sharply defined with slits, then the sensitive volume will be small. Typically, it will be ellipsoidal and elongated in the Z direction as indicated in Fig. 1. This will be called the Type I configuration below. On the other hand, if a broad sensitive volume is desired, the slits can be widened or eliminated. Efforts to produce a sensor with a broader sensitive region, called a Type II configuration, will also be described.

A breadboard sensor was constructed for laboratory evaluation but it was configured somewhat differently than Fig. 1. A sketch, drawn approximately to scale, showing the arrangement of parts is given in Fig. 2. The optic axes of illuminator and detector are parallel, and a separate prism is placed in front to converge the beams at the desired focal point. By such an arrangement the body of the sensor can be of fixed design, while a large range of focal distances can be accommodated by modifying the prism. In the present device, the illuminator is a Gallium arsenide LED radiating at 0.94 μ, [11] and the detector is a Silicon photodiode. [12] A photograph of the sensing head is shown in Fig. 3.

Experience to date is with the prism configuration of Fig. 2, but we feel that replacement of the prism by a segment of a simple lens would yield significant improvement in resolution and convenience. The separate illuminator and detector lenses would then be focused at infinity. The prism would be replaced by a lens having a focal length equal to the desired sensitive distance. Future experiments will also be made with such a configuration.

The light returned from the LED source was detected in the presence of normal background illumination both by using an optical filter and by pulsing the light source. The filter is a long-wavelength-pass filter [13] which rejects all visible light, and has a transmission of 83% at 0.94 μ. A properly matched narrow band interference filter would be more effective, but was not found to be necessary. The light source was pulsed at a 1500 Hz rate with a 50% duty cycle (square wave). The pulse current was 50 ma. The desired photosignal was then extracted with well-known phase-detection techniques. A block diagram of the electronics is given in Fig. 4. The electronics can be carried on one standard 10 x 15 cm circuit board.

Laboratory Results

Sensor output was determined as a function of the position of a white surface along the Z axis. Cross-axis output profiles were determined by moving the edge of a card laterally across the beam. To obtain curves more comparable to the Z axis data, the transverse output curves were differentiated, yielding relative sensitivity for a narrow pencil shaped target as a function of position. The simulated narrow target would be oriented parallel to the x axis and moved along y for the y profile, or vice versa.

Output profiles are shown in Fig. 5, for a Type I configuration. The magnitude of the output signal is proportional to the reflectivity of the sensed surface. The full width of the observed peak at half maximum is 24 mm along Z, the sensing direction. At the peak, Z = 7.5 cm, the width was 5 mm along Y and 0.5 mm along X. Therefore, the sensitive volume may be approximated by an ellipsoid 24 mm x 5 mm x 0.5 mm. The larger width along the Y dimension is due to the finite slit length. The flat-topped Y profile seen in Fig. 5 is also compatible with the finite slit length.

The theoretical size of the sensitive volume for a Type I configuration can be calculated from known geometrical factors. The sensitive ellipsoid should measure approximately 6 mm along Z, 3 mm along Y, and x 0.4 mm along X. This is in reasonable agreement with observation for the X and Y dimensions, but the observed Z dimension is larger than calculated. Imperfect focusing probably causes the disagreement.

In a second experiment, an attempt was made to obtain a sensitive volume extending from the focal point inwards to the point of contact; the Type II sensor. One side of the detector slit was removed, widening the geometrical overlap between the two beams. In addition, prismatic facets similar to a fresnel lens were cut in the prism as shown in Fig. 6, so that a portion of the radiated light was directed across toward the detector field inside of the nominal focal zone. Similar facets were placed over the detector lens to collect radiation returned from this region.

The result is shown by the raw sensor output curve in Fig. 7a. The nominal focus is 7.5 cm as in Fig. 5, but the output profile has been extended inward considerably. Refinement of the prism modification will yield further flatenning of the Z axis response. The lateral dimensions of the sensitive volume are similar to Fig. 5 at the design focal distance of 7.5 cm, but increase at closer distances. The approximate location of the sensitive volume for both the Type I and the corresponding Type II configuration is sketched in Fig. 8. An ideal Type II output can be obtained by increasing the gain of the signal channel and at the same time limiting the output. The result is shown in Fig. 7b, as observed in the breadboard sensor. The difference between white and black surfaces is larger than it should be, and is due to inexact focusing, which also produces the long tail seen in Fig. 7a. A range of ~1/2 cm between black and white surfaces at $Z_o = 7.5$ cm should be achievable.

The average radiated power from our sensor was approximately 10^{-5} watt. With this power level, calculations show that detection to 1 to 2 meters is possible, based on the known detector sensitivity and the geometry shown in Fig. 2. With a larger collecting lens and using an injection laser to replace the LED, detection to 100 m would be possible. Thus, sufficient light intensity for a few-centimeter sensing distance is readily obtainable, and similar sensors could be set up for much larger distances if desired.

Discussion

Our experience indicates that an optical proximity sensor small enough for convenient use on an effector can readily be made. Two configurations, Type I and Type II, are suggested, Type I having a sharply defined sensitive volume and Type II an extended one. Design of a Type I sensor is straightforward. We feel that the Type II configuration, one more suitable for analog control purposes, is equally feasible, although further work is necessary to smooth its response curve.

Either type can cover a range of focus distances from, say, 1 cm up to roughly 1 m by suitable choice of a replaceable prism or lens.

Since with a fixed lens spacing the convergence angle of the two light cones varies inversely with the focal distance Z_o, the length of the sensitive volume (for Type I) will be proportional to $1/Z_o^2$. Representative figures were given above for the $Z_o = 7.5$ cm breadboard sensor. This sensor was easily able to detect an isolated 0.3 mm diameter string near its focus. Our present experimental sensing heads are 20 mm x 15 mm x 10 mm in overall size, but the detector and LED themselves are small enough that considerable reduction in size could be obtained without change in the basic sensor layout. A package 10 mm x 10 mm x 5 mm would be a reasonable goal, assuming somewhat smaller lenses. Beyond this, integrated circuit technology is applicable to both LED and detector, and could offer a totally new dimension in miniaturization. Arrays of sensors, or digital position determination by stacking Type I sensitive volumes would become possible.

The effect of variations in surface reflectivity on the sensor output was mentioned earlier. Since output is basically proportional to reflectivity, if the slope of the output curve is to be used as an indicator of position, a white surface must appear to be closer than a black one. Although it is possible to encounter a factor of perhaps 20 in reflectivity between whitest and blackest surfaces, a factor of three is a more reasonable range for natural materials (from $R = 0.2$ to 0.6).

It is feasible to eliminate the effect of reflectivity at the expense of added complication. For example, a separate detector could be added to essentially monitor reflectivity, providing information which could compensate for such changes by appropriate signal processing. However, a simpler approach would be to attempt to devise control schemes which can tolerate the expected reflectivity range.

It may be useful here to comment briefly on the possible types of data obtainable from a proximity sensor because of a close relationship to the effect of reflectivity variations. The Type I sensor is basically a device which detects the presence of a surface in a certain region. The output is one bit of information; object present, or no object. Reflectivity is of minor importance here, since the detection threshold can be set low enough for the darkest surface. Similarly, a Type II sensor having an appropriately focused slit system could yield an output curve with a sharp slope at a focal distance Z_o, as in Fig. 7b. The distance Z_o would be geometrically determined, and not strongly dependent on reflectivity. On the other hand, the Type II sensor can be set up to have an extended slope, leading from zero to a saturated output as the object surface approaches contact. This would be accomplished by defocusing and widening of the slits. In this case, surface reflectivity enters directly into the relation between sensor output and the position Z of the surface. Finally, if a control scheme were devised in which the peak of the Type I sensor output versus position is detected, the result would be rigorously independent of reflectivity.

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11. RCA Type 40844.

12. Hewlett Packard Type 4204.

13. Wratten, No. 87C

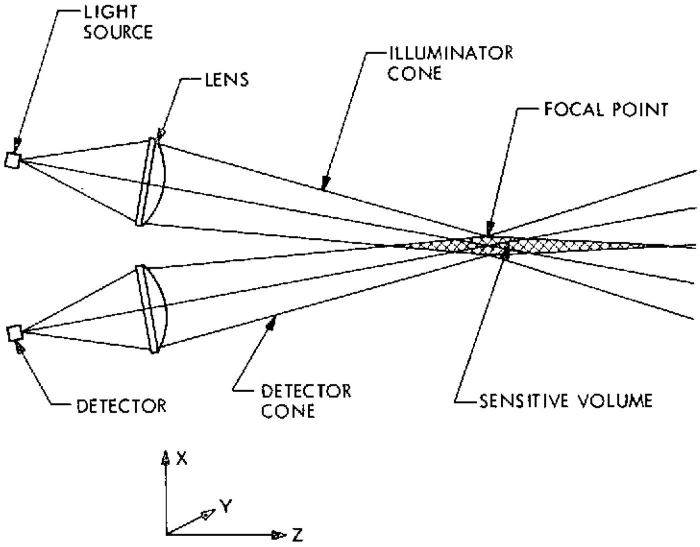

Fig. 1. The proximity sensor concept

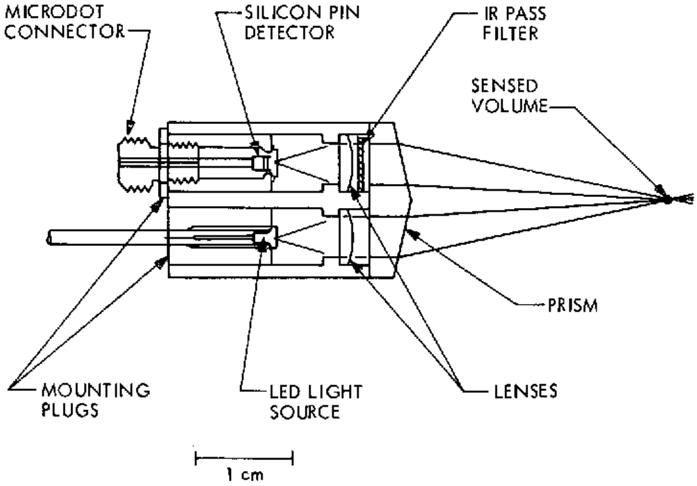

Fig. 2. Detailed sketch of the breadboard sensor showing the replaceable prism element

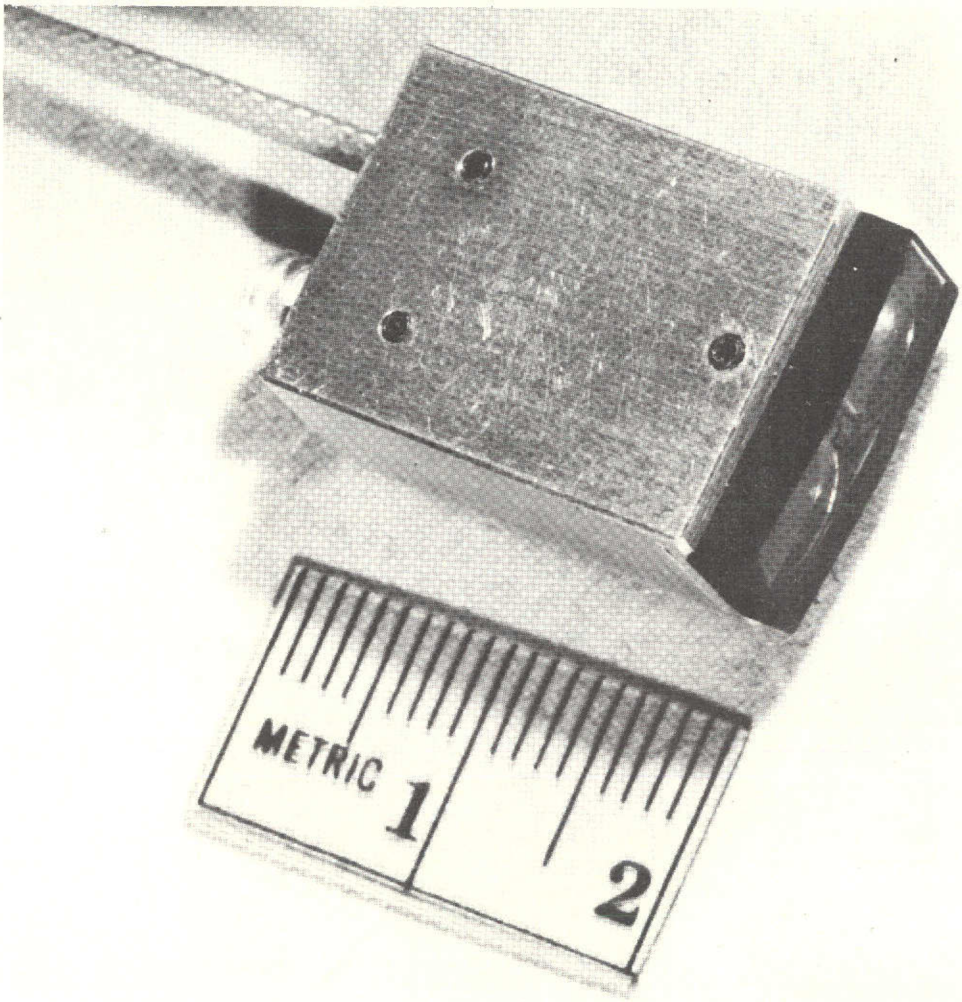

Fig. 3. Photograph of proximity sensor head

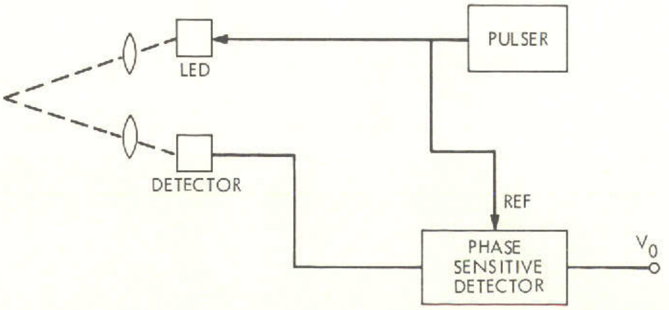

Fig. 4. Block diagram of the electronics

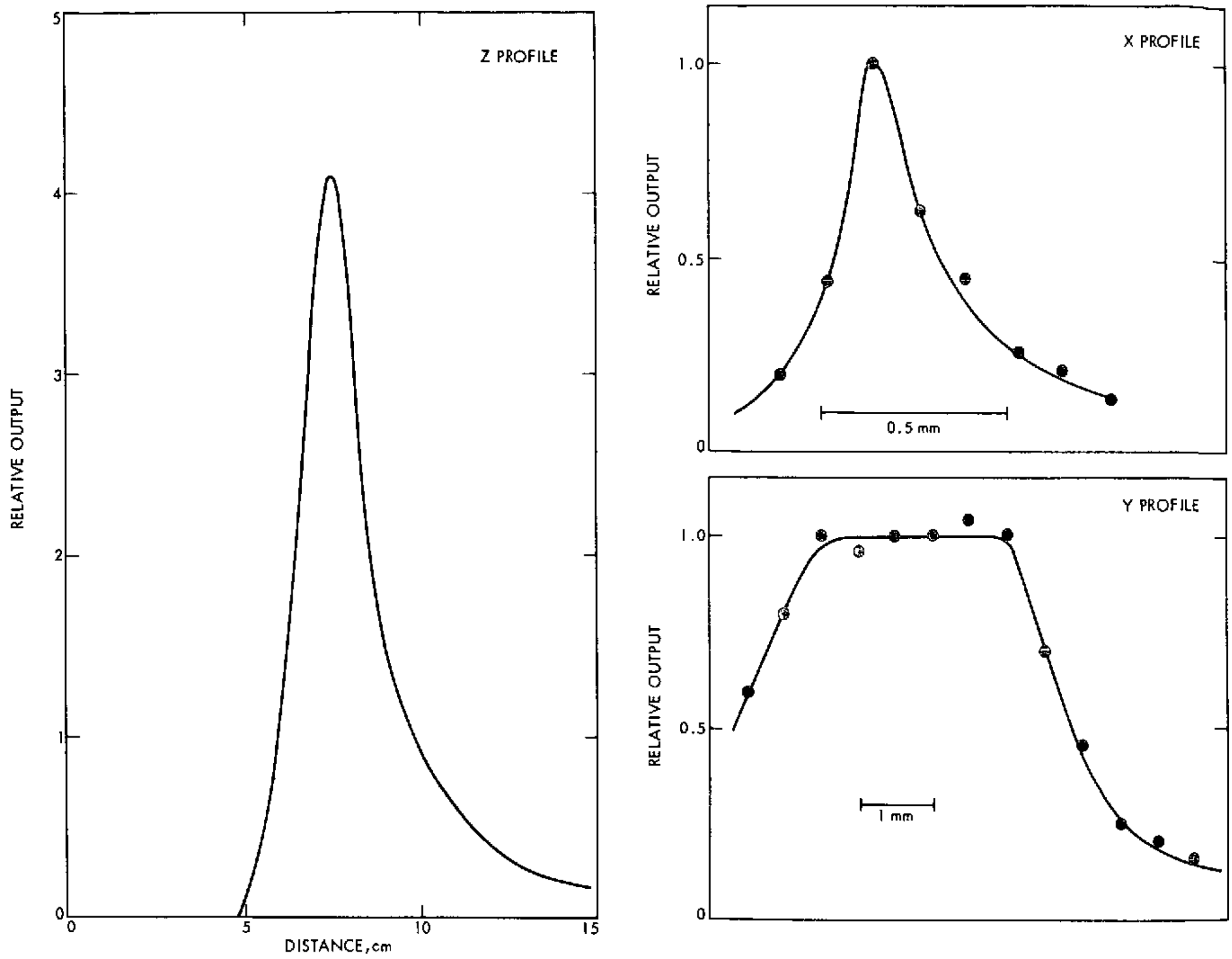

Fig. 5. Output profiles of a Type I (sharply defined sensitive volume) sensor. The x, y, z coordinates are as indicated in Fig. 1. The transverse X and Y sensitivity profiles were made at the peak of the Z profile, Z = 7.5 cm

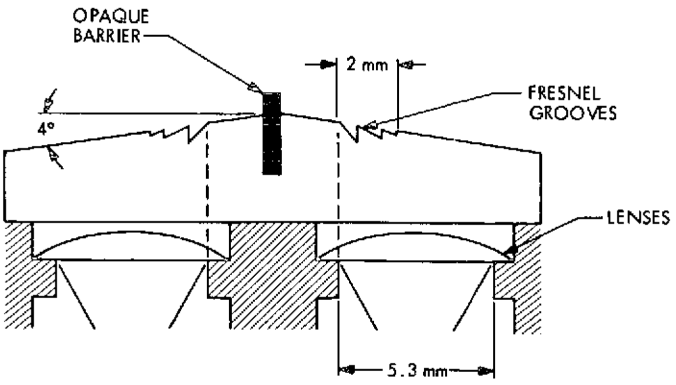

Fig. 6. The prism modification used in the Type II sensor

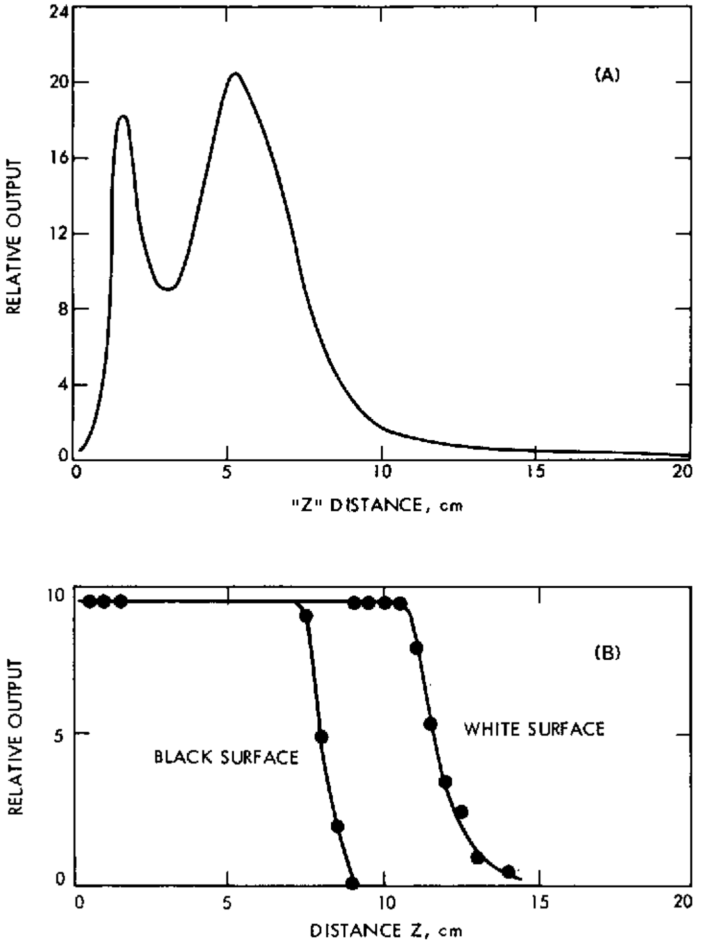

Fig. 7. Output profiles for a Type II configuration. The focal distance Z is 7.5 cm, but a set of prismatic facets on the prism as shown in Fig. 6 extend the sensitive volume inward: (A) the raw sensor output; (B) the result of increasing the gain and limiting the sensor output, with experimental curves for both a black and a white surface

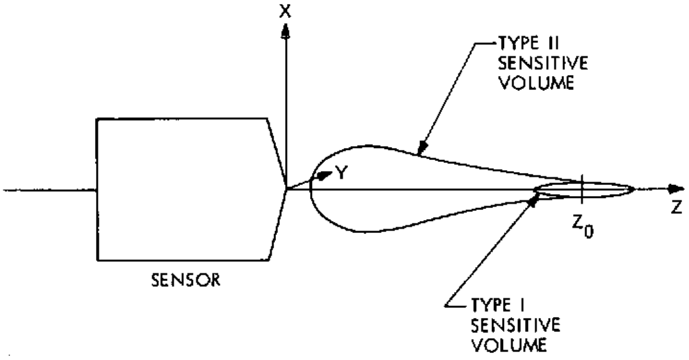

Fig. 8. Diagram showing approximate location of the sensitive volume for both Type I and Type II configurations

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