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Abstract

This paper describes design and development of two types of 3-D ranging devices for robotic applications: both are noncontact, optical devices based on active illumination and triangulation. One is a laser scanning ranging device for medium-range (50cm), and the other is a proximity range sensor for short range (5 cm). The features of the devices are that both use analog area position sensor chips and that they provide simple, fast, accurate, non-contact visual sensing of range information.

1. Introduction

For robotics applications, sensing of three-dimensional range information of the object relative to the manipulator is very important. Range sensing can include distance, surface orientation, surface curvature, and even surface properties. Range sensing is still a slow and costly process. The basic principles for optical range-sensing are: passive illumination and triangulation (stereo [3]); active illumination and triangulation (e.g. bar-of-light [6] [1]); and time of flight [5].

This paper describes two types of 3-D ranging devices for robotic applications, based on active illumination and triangulation, which are being developed at Carnegie-Mellon University. One is a laser scanning ranging device for medium-range (50cm), and the other is a proximity range sensor for short range (5 cm). The features of the devices are that both use analog area position sensor chips and that they provide simple, fast, accurate, non-contact visual sensing of range information.

2. Scanning Laser Ranging Device for Medium Range

2.1. Configuration

Figure 1 shows a schematic diagram of the device we are building. It basically consists of: a laser, a pair of rotation mirrors; and a spot position detector. The laser is a 15 mW He-Ne laser with a beam of 1.1 mm diameter and 1.0 milliradian divergence angle. The pair of tiny mirrors are for deflecting the laser beam. They rotate around orthogonal axes. Each mirror is mounted on a galvonometer axis. The angle of the mirror is determined by the current supplied to the galvonometer. The maximum angle of rotation is 12^{o}. The distance from the laser to the object is about 1 m. Therefore we can scan an area of 21 cm × 21cm.

The spot position detector is placed at a distance of about 50 cm from the object. It consists of optics (actually a monolens camera), a position sensor chip mounted at the film plane of the camera, and a simple circuit. The position sensor chip is a photo sensitive planar PIN diode [2]. Unlike a vidicon camera or a CCD array, it is an analog area sensor (no scanning). With simple calculation, output currents to its four electrodes directly tell the position of an intensity spot projected on a sensitive field of the chip. We use an LSI-11/23 to control the device: it controls the angles of the mirrors and reads in the output of the position sensor after digitization.

2.2. Principles and Design Considerations

Triangulation

The principles are basic triangulation. Refer to Figure 1. The laser beam is reflected by the two (x and y) orthogonal mirrors and can be oriented to an arbitrary direction in the 3-D space. The angles are controlled by the computer program. The laser beam hits the surface of the object and a bright spot is observed. The spot is sensed by the spot position detector. The direction of the emitting beam is controlled, and the direction of the view line is detected. Thus we can determine the

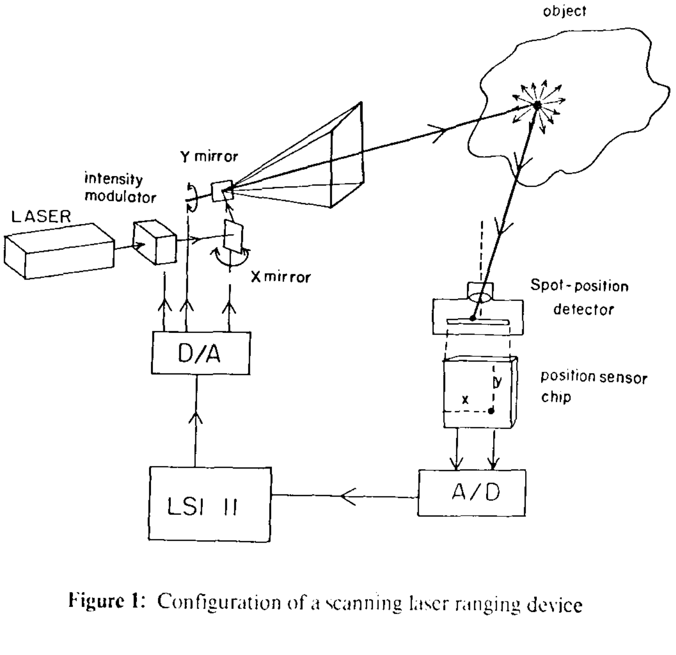

Figure 1: Configuration of a scanning laser ranging device

position of the spot in 3-D space.

Position Sensor Chip and Circuit

Figure 2 shows (a) a schematic diagram, and (b) a simplified equivalent circuit of the position sensor chip. Conceptually it is two layers of homogeneous resistance network. A current source I_0 emerges at the position where a spot of light is projected. Imagine that a spot light exists at (x,y), $0 \leq x \leq 1$, $0 \leq y \leq 1$, on the chip and that the outer circuit is closed with balanced load resistances R_0, as shown in Figure 2(b). The currents I_{x1}, I_{x2}, I_{y1} and I_{y2} are then given:

$$
\begin{aligned}
I_{x1} &= \frac{rx+R_0}{rx+r(1-x)+2R_0} I_0 = \frac{rx+R_0}{r+2R_0} I_0 \\
I_{x2} &= \frac{r(1-x)+R_0}{r+2R_0} I_0 \\
I_{y1} &= \frac{ry+R_0}{r+2R_0} I_0 \\
I_{y2} &= \frac{r(1-y)+R_0}{r+2R_0} I_0
\end{aligned}
\qquad (1)
$$

Thus when we compute

$$
\begin{aligned}
X &= \frac{I_{x1}-I_{x2}}{I_{x1}+I_{x2}} = \frac{r(2x-1)}{r+2R_0} \\
Y &= \frac{I_{y1}-I_{y2}}{I_{y1}+I_{y2}} = \frac{r(2y-1)}{r+2R_0} \\
I_0 &= I_{x1}+I_{x2} = I_{y1}+I_{y2}
\end{aligned}
\qquad (2)
$$

The values X and Y give the position of the spot (x,y) in the field of view.

Actually the load resistance R_0 is realized as a current-to-voltage converter, shown in Figure 3. The value of the feedback resistance R_b determines the conversion factor $B = V_{out}/I_{in}$. It also relates to the equivalent input resistance of the circuit (load resistance to the chip) $R_0 = R_b/A$, where A is the open loop gain of the operational amp. Notice from equation (2) that R_0 should be small enough compared to the resistance of the chip for accurate measurement. Also, a smaller R_0 gives a faster response time.

In our set up, we use a 15 mW laser as a light source, and return of light is sensed at a 50cm range. The opening of the lens is 1.4 cm radius. Thus, assuming uniform reflection over a half hemisphere and a white (high reflectivity) object surface, the amount of received intensity can be estimated as

$$\frac{(1.4)^2}{(50)^2} \times 15 \times 10^{-3} W \sim 12\ \mu W$$

This amount is larger than the minimum intensity ($\sim 2\ \mu W$) required for this chip to operate. This intensity will generate current (I_0)

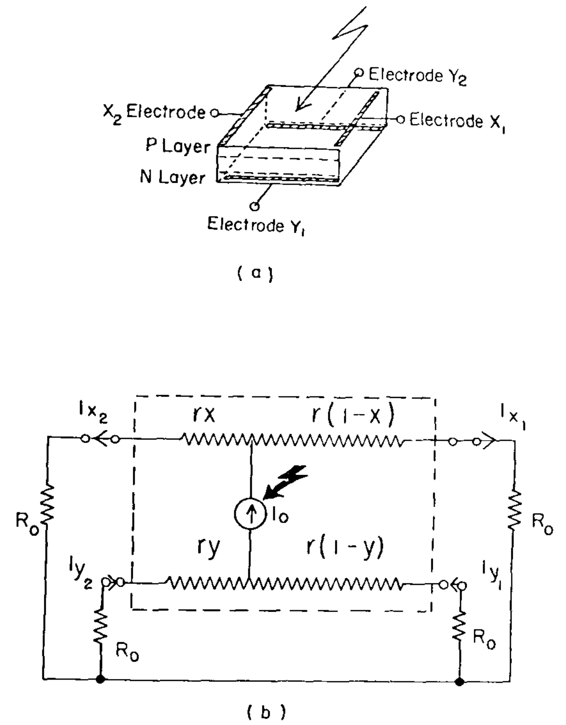

Figure 2: Analog position sensor chip [2]

of about 20~40 μA. The R_b was set 100KΩ: we have 2~4 Vp-p signal at the output. The open loop gain A of our operational amp is 100dB; the equivalent input resistance R_0 is $10^{-5}\Omega$. We can expect the rise time of the response signal to be less than 10 μsec.

2.3. Features

Simplicity

Unlike the case of using a vidicon or CCD camera, we do not need to scan the field of view, nor do we need any sophisticated data processing capability, such as an algorithm for spot detection in an image.

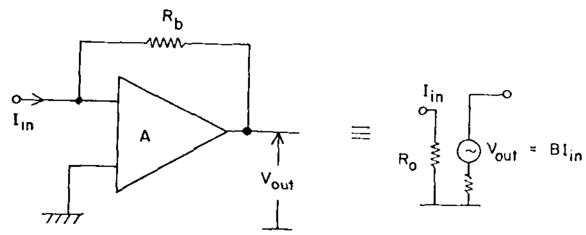

Figure 3: Current-to-voltage converter

Speed, Random Scan and Accuracy

As seen from the above description of operation, the cycle time for the measurement of one point is from directing the laser beam to detecting the location of the spot. It seems that the sensor chip we are using can safely operate within 100 μsec~200 μsec for a point, or, 10,000 to 5,000 points/sec. In this regard, we can see the advantage of using the position sensor chip over a TV camera. The latter scans the field of view to detect one spot in it, which takes 1/30 sec. One can use the bar-of-light method [6], so that one measurement for each TV scan line can be done during one frame: then, assuming 250 lines in one frame, up to 7,500 points/sec. can be sampled (but, this needs special hardware which detects the position of light in each scan line at a video rate.)

This device can provide random-scanning capability for range sensing. The limiting factor, however, is the rotation of the mirror, because we use electro-mechanical galvanometers. Faster scanning devices or opto-acoustic devices for deflection are available. We have not checked out the accuracy yet, but we expect a resolution of 1000 lines across the chip.

Insensitivity to Defocus

The output of the analog sensor chip essentially tells the gravity center of intensity. This means that even if the spot image is blurred, the output of the chip does not vary much. The range measurement is thus relatively insensitive to defocus, which is an important feature.

This feature is also useful to cope with deformation of spot shape due to surface orientations. When the laser beam hits a slanted surface, the reflected spot is of an elongated elliptical shape. Detecting the center position of an elliptical spot is not trivial when using a TV camera, but this chip performs that task intrinsically, due to its physical characteristics.

Reflectivity Measurement

The total current I_0 in the equation (2) provides the possibility of measuring the surface reflectivity for certain classes of surfaces. Since we have a single light source (a laser), the value I_0 is proportional to the spot intensity; i.e., the amount of light which is reflected at the surface and reaches to the sensor. In the simplest case in which the object surface is Lambertian, it is proportional to the reflectivity (ρ) multiplied by the cosine of the incident angle of light (θ). See Figure 4. That is,

$$I_0 \propto \rho\cos\theta. \qquad (3)$$

Notice that we can compute $\cos\theta$. θ is the angle between the local surface normal and the light: the local surface normal can be obtained from the measured range data, and the direction of the laser beam is known. Therefore, the reflectivity at each point of the surface can be obtained by $\rho \propto I_0/\cos\theta$. This means that this device can provide not only measurement of the object shape but also the intrinsic brightness (reflectivity) pattern of the Lambertian object surface.

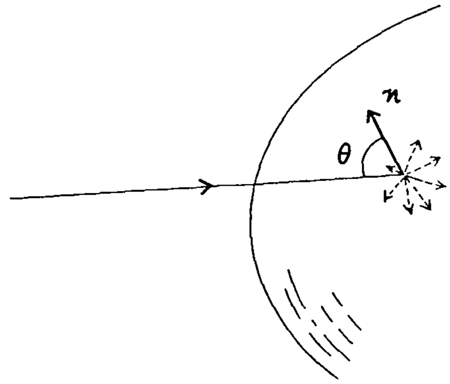

Figure 4: Reflectivity measurement

3. Noncontact Visual Proximity Sensing Device

3.1. Configuration

We are also developing a triangulation-based visual proximity sensor which uses LEDs and the same type of position sensor chips. The basic configuration is shown in Figure 5. The device consists of a set of light sources and a spot position detector. A set of light sources are placed certain geometrical arrangement. In the prototype device we have constructed, six infrared LEDs are placed circular ring, 60° apart, so that they form a cone of rays. In other words, they are placed in a circularly around the optical axis so that their rays converge at a point on the camera-lens axis (the cone axis). The converging point (tip of the cone) is set at the middle point of the range of interest in front of the device. Each

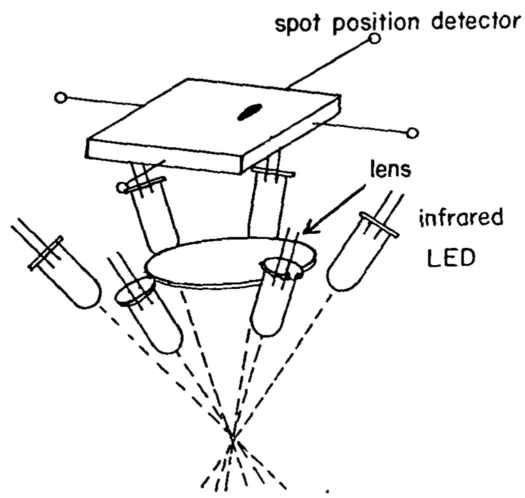

Figure 5: Configuration of a proximity ranging device

LED can be turned on and off independently. A spot-position detector detects the location of a spot in the field of view. It uses exactly the same position sensor chip and the circuit as the laser scanning ranging device in the previous section.

3.2. Operation

Distance Measurement

Suppose that the objective surface is within the measurement range of the device. Each LED is turned on and off sequentially, one at a time, so that no more than one is projected on the surface at the same time. Therefore the location of the spot is easily detected as the center of intensity in the image. Since the direction of the emitting ray and the line of the view to the reflected spot are both known at each time, the 3-dimensional position of the spot (i.e., a point on the surface) can be calculated by the principle of triangulation.

Surface Orientation Measurement

This proximity sensing device, however, can do more than simple distance measurement. It can exploit the fact that it has redundant multiple light sources. They can be turned on in a particular order, so

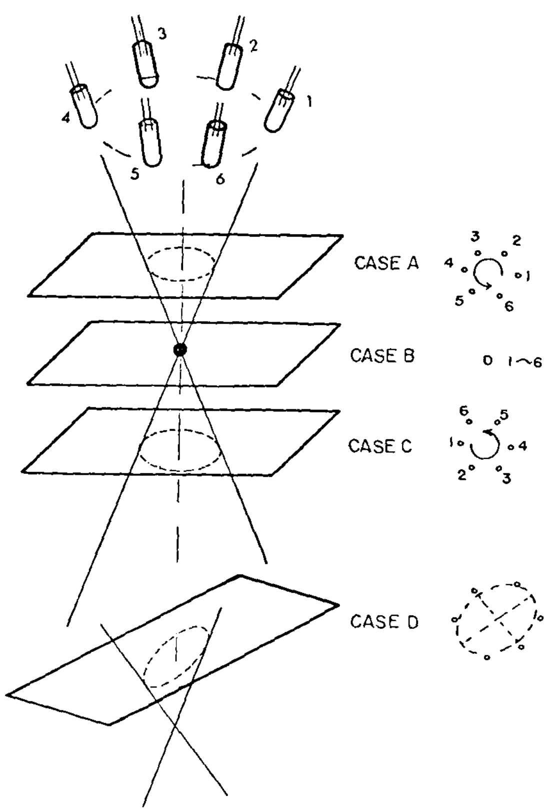

Figure 6: Principle of surface-orientation measurement

that the information, such as distance and orientation of the surface, can be extracted in a most reliable way. Introduction and exploitation of the redundancy is an essential advantage of this device over a device which uses a single light source and a one-dimensional sensor, such as [4]. We will explain the basic idea by referring to Figure 6. Imagine the case in which the surface is perpendicular to the camera-lens axis. If the surface is just at the converting point (case B), the image projected by the cone of the rays from the LEDs will be a point. If the surface recedes beyond (case C) or advances in front of (case A) the converging point, the image will be a circle; its radius is proportional to the distance of the surface from the converging point. Actually, rather than lighting all the LEDs simultaneously, we light them one by one to rotate the rays in the cone. Then the image points will rotate in the same phase if the surface is closer than the converging point (case A), and in the phase shifted by 180°, otherwise (case C). Further, if the surface is slanted relative to the axis of the camera-lens (case D), the image will be an ellipse whose principal axes give the orientation of the slant (case D).

3.3. Design Considerations

Infrared LEDs

The position sensor chip is most sensitive in the infrared range (800-1000 nm). We use infrared LEDs whose wave length of peak emission is 940 nm. Since we turn them on intermittently, the LEDs can be pulsed and overdriven to give higher intensity, thus resulting in better S/N.

Geometry

Let us discuss how we can design the geometry of the device. As shown in Figure 7, let us think about a plane which includes the optical axis and an LED. Take the x-z coordinate axes as shown. LEDs are placed on a plane perpendicular to the z axis. Their rays point to (0,d) on the z-axis. θ denotes the angle that the LED beam makes with the z axis.

Suppose that the optical system is designed so that the plane $z=d$ through the converging point is at the best focus and that the plane is imaged on the sensor chip with a magnification factor M. To model this imaging geometry we can imagine the sensor chip is at $z=-Md$. Then a spot at (x,z) generates its image on the sensor at x_m,

$$x_m = \frac{x}{z} Md \qquad (4)$$

The equation of a beam is,

$$z = (d\tan\theta - x)\cot\theta \qquad (5)$$

Since the spot is on the beam, we obtain from (4) and (5) the depth (z) as a function of the spot image location (x_m).

$$z = \frac{d}{1 + x_m/Md\tan\theta} \qquad (6)$$

The sensitivity of the depth measurement can be evaluated by the amount of change in x_m due to a change in z. From (6),

$$\frac{\Delta x_m}{\Delta z} = \frac{d^2 M \tan\theta}{z^2} \quad (7)$$

$$S = \frac{\Delta x_m}{\Delta z}\Big|_{z=d} = M\tan\theta$$

S is sensitivity at $z = d$. The larger the S is, the more sensitive the measurement. Naturally, as (7) shows, the larger magnification and the more slanted beam give a greater sensitivity.

We can measure a range of depth from z_1 to z_2, which correspond to the cases that spot images are at the edge of the effective sensor field, i.e. $x_m = L$ and $x_m = -L$. The maximum measurable range D is given as,

$$D = z_2 - z_1 = \frac{2(L/S)}{1-(L/Sd)^2} \quad (8)$$

Usually, in designing this device, d (depth of interest) is given. M (magnification) and θ (beam angle) are design variables that have to be determined. The trade-off in determining M and θ is between D (measurable range of depth) and S (sensitivity). The larger M and θ we choose, we have the larger S but smaller D, and vice versa. Practically, however, D can not be too large, because it has to be within a range of reasonable focus and distortion due to lens. θ also should not be too large, because, if so, the amount of return light tends to be very small.

In the prototype device we have constructed, we have chosen the following values:

depth of interest:	$d = 45$mm
chip size:	$2L = 8$ mm
magnification:	$M = 1$
beam angle:	$\theta = 45°$
max. depth range:	$D = 16$ mm (usable range $\approx$ 10mm)
sensitivity:	$S = 1$

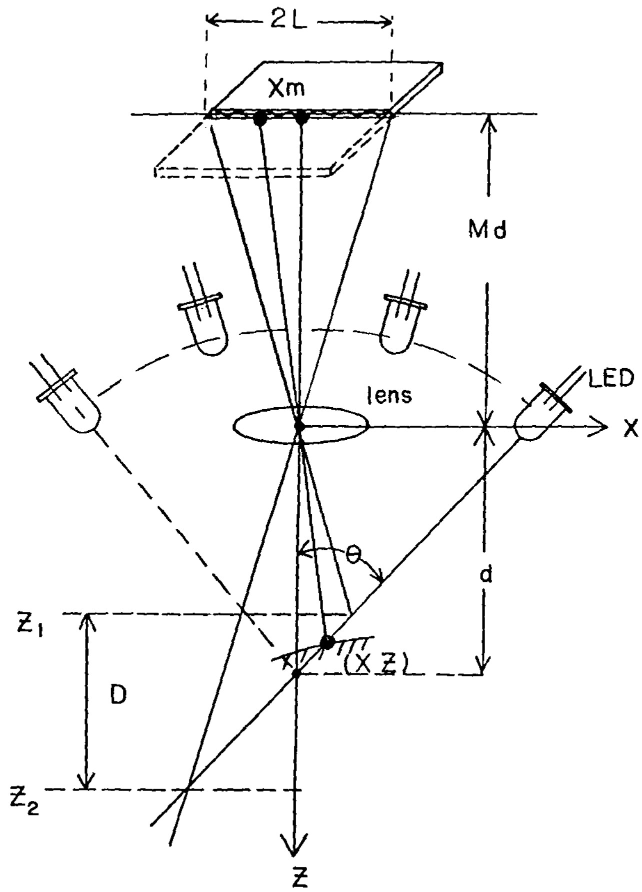

Figure 7: Geometry of distance measurement

3.4. Features

Simplicity

The sensor head of the device consists of only LEDs, simple optics, and a position sensor chip. The prototype device weighs only 55g.

Speed and Accuracy

The device has no moving parts. It can operate at the maximum speed of the sensor chip: safely 5,000 points/sec or 830 orientations/sec. The device includes nonlinearity of the sensor chip, distortion by the lens, and effect of defocus. However, since they are fixed over time, we can calibrate beforehand and compensate them when computing the distance and orientation. Another important feature is that the accuracy in measurement can be substantially increased, either by using the redundancy in the LED configuration, or by pulsing the LEDs and averaging results.

Reflectivity Measurement

This device also has the capability of measuring the reflectivity by the same principle as in the scanning laser ranging device. We can expect better S/N and a larger dynamic range in this case. One reason for this is that the intensity of return of light is higher because the objective surface is closer. The other reason is that when we attach this sensor to the end effector of a robot arm, we can control the arm (using the measurement by this device) so that the sensor's axis is perpendicular to the objective surface in which case the measurement is most accurate.

Extensible Ideas

What we have presented here is the very basic idea. Various modifications can be designed for devices for particular applications. One possible change is the arrangement of the LEDs. For example, the present device has a circular arrangement of LEDs. This, however, is incapable of measuring surface curvature, because surfaces with opposite signs of the second derivative at the optical axis will give the same measurements. To measure curvature, double circular rings of LEDs with closer and farther converging points will work. Also, for the purpose of tracing edges, arrangement of LEDs in two parallel lines will be suitable.

Another possible variation is the order of lighting the LEDs. Imagine the case that the object moves relative to the sensor. Depending on the direction and speed of the motion, we can program and control the most suitable order of lighting to have the best results.

4. Conclusion

Design and development of two types of ranging devices have been presented: one is for 50 cm range and the other for 5 cm range. Both use the same type of analog position sensor chips to detect spot locations. They have features of simplicity, speed, and measurement of range and reflectivity. Prototypes of both devices have been constructed. We are collecting data to evaluate their performance.

These devices are useful for various robotic applications. The first applications we are working on are measurement of object shape using the laser scanning ranging device, and trace of surface by a robot arm, keeping the same attitude by using the proximity sensor.

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