The paper focuses on the design and performance of new proximity sensors. How will the type of sensor can measure the orientation of a target surface depend on the number of projected light spots, and how they are oriented with respect to each other? To use this in practice, we can measure the performance of a target surface.

1. Introduction


e to detect the presence of a target surface. The sensor uses optical proximity sensors and provides a range of 0 to 100 cm. The sensor uses the distance of approximately 200 cm to determine the distance of the target surface. The sensor uses a pattern of light spots to detect the target surface's orientation. The sensor uses the projection of light spots to determine the distance of the target surface. The sensor uses the projection of light spots to determine the distance of the target surface. The sensor uses the projection of light spots to determine the distance of the target surface. The sensor uses the projection of light spots to determine the distance of the target surface. The sensor uses the projection of light spots to determine the distance of the target surface. The sensor uses the projection of light spots to determine the distance of the target surface.

This sensor may be used as a robot manipulator to home in on a target surface with a precision of 0.1 mm. When the target surface is detected, the sensor measures the distance of 0.1 mm and 100 cm. When the target surface is detected, the sensor measures the distance of 0.1 mm and 100 cm.

We have developed a new sensor that can measure the range and shape of a target surface. The sensor uses the projection of light spots to determine the distance of the target surface. The sensor uses the projection of light spots to determine the distance of the target surface.

Abstract

Alcoa Corporation

Equipment Development Division

1509

Alcoa Proprietary

and

Philippines, P.O. 1924

Can use Surface Sensors and Hotspot Indicators

Takeo Kanade and Michael Frumin

for Measuring Surface Shape

A Noncontact Optical Proximity Sensor
distributed. Hence, the new sensor was designed with the aid of a statistical argument that takes into account the geometry of the sensor to minimize measurement uncertainty. The performance of the sensor was tested by measuring the distance and shape of various target surfaces.

2. Measurement of Distance and Shape

2.1. Overview

The proximity sensor is based on the principle of active illumination and triangulation. Figure 1 shows the basic configuration of the proximity sensor head in this drawing consists of a ring of light sources, a lens, and a light spot position sensor chip.

![Figure 1: Configuration of the Multi-Light Source Proximity Sensor](image)

The principle of operation is as follows. A beam of light emitted from the sensor head is interrupted by a target surface. The resultant light spot on the target surface is focused by the lens onto the analog light sensor that is sensitive to the intensity and position of a light spot in its field of view. Since the direction of the incident beam of light is known, and the light sensor measures the location of the light spot in the field of view, the three dimensional (3-D) coordinates of the light spot on the target surface can be computed by triangulation. The proximity sensor has multiple light sources, and as a result the coordinates of several discrete points on the surface can be measured. The average distance, orientation, and curvature of the target surface are computed by fitting a plane and then a quadric surface to this set of points.

Three features of the analog sensor chip make it an attractive device for use in the proximity sensor: its position linearity, its intrinsic ability to measure the centroid of a light spot on its surface, and its speed of response. The chip, a planar PIN diode, measures both the intensity and the position of the light spot on its surface. If the spot of light on a target surface is distorted because of the curvature or orientation of the surface, the sensor chip responds to the stimulus by measuring the coordinates of the centroid of the image of the light spot. To minimize error when computing the coordinates of the light spot, the spot size must be kept small. Therefore, light emitting diodes (LEDs) are used that have a light source diameter of about 150 \( \mu \text{m} \).

2.2. Measuring the Distance of a Surface

The coordinates of a light spot on a target surface are computed by triangulation. The trajectory of each light beam that illuminates a surface is fixed and is measured in advance. The line of sight to the light spot on the target surface is obtained from the sensor chip. The calculation of the coordinates of the light spot is based on a simple optical model: first, the light source beam is a line, and thus the projected light spot is a point; second, the camera lens forms a flat, undistorted image; and finally the sensor chip is linear in finding the light spot position and is insensitive to defocus. Since the sensor is subject to small errors because of deviations from the simple model, they are treated as perturbations from the model and error corrections are calculated beforehand.

The position and orientation of a line in 3-D space can be defined by the
choose the common coordinates of the light spot to lie on the light beam.

After solving for $a$ and $b$, the coordinates of the light spot can be chosen.

(1) $\mathbf{a} \cdot \mathbf{v} = 0$

(2) $\mathbf{b} \cdot \mathbf{v} = 0$
2.3. Surface Fitting

To estimate the position and orientation of a surface, a plane is fit to the set of three-dimensional data points obtained by the proximity sensor. To estimate the curvature of a surface, a second order equation is fit. The accuracy of the calculation of position, orientation and curvature depends, therefore, on the accuracy of the individual data points, and the number and distribution of the data points on the surface. For example, if the points are too closely spaced, the orientation of the plane that is fit to the points will be very uncertain. These relationships were analyzed, and the results were used to design a sensor whose expected uncertainties are less than the design specifications.

Suppose there are $n$ measured points on a surface, where each point $(x_i, y_i, z_i)$ has an estimated total uncertainty in position of $\sigma_i$. A surface can be fit to this set of points using the method of least squares to determine the coefficients $a_j$ in the equation

$$z(z_i, y_i) = \sum a_j X_j(z_i, y_i)$$

where $X_j(x, y)$ is a polynomial of the form $\sum c_{ij} x^i y^j$, as for example, when fitting a plane, $q + r \leq 1$, and when fitting a quadric surface, $q + r \leq 2$. We are concerned with how the uncertainty in the measured points and their distribution on the surface affects the uncertainty of the computed coefficients.

The values of the coefficients $a_j$ are chosen so that they minimize the aggregate error $E$:

$$E = \sum_{i=1}^{n} \left( \frac{1}{\sigma_i^2} (z_i - z(x_i, y_i))^2 \right) = \sum_{i=1}^{n} \left( \frac{1}{\sigma_i^2} (z_i - \sum a_j X_j(x_i, y_i))^2 \right)$$

By minimizing $E$, each $a_j$ can be computed by:

$$a_j = \sum_k \varepsilon_{jk} \beta_k$$

where

$$\varepsilon_{jk} = [\alpha_{jk}] - 1$$

$$\alpha_{jk} = \sum_{i=1}^{n} \left( \frac{1}{\sigma_i^2} X_j(x_i, y_i) X_k(x_i, y_i) \right) = \frac{1}{2} \frac{\partial^2 E}{\partial a_j \partial a_k}$$

$$\beta_k = \sum_{i=1}^{n} \left( \frac{1}{\sigma_i^2} X_k(x_i, y_i) \right)$$

The symmetric matrix $[\alpha_{jk}]$ is known as the curvature matrix because of its relationship to the curvature of $E$ in the coefficient space [4].

We can estimate the uncertainties of the coefficients, and determine their dependence on the geometry of the proximity sensor if we assume that fluctuations in the coordinates of the individual data points are uncorrelated, and assign the total uncertainty in the measurement of position to the variable $z$. The uncertainty of the coefficient $a_j$ is then

$$\sigma_{a_j}^1 = \sum_{i=1}^{n} \sigma_i^q \frac{\partial a_j}{\partial z_i}$$

By calculating the partial derivatives of Equation (7), it follows that the uncertainties of the coefficients are proportional to the diagonal elements of the inverse of the curvature matrix [4], that is

$$\sigma_{a_j}^2 = \delta_{jj}$$
Figure 3 shows the proximity sensor over a target surface. The projected
of the sensor,

convolutions of \( \phi \) and \( \psi \) can be computed where the surface intersects the ads
in particular, the normal curvature, \( \kappa_n \) and the principal normal
surface can be computed at any point from the coefficients of the Gaussian.

On a surface is in the set of data points. The curvature of the target

\[ f + g + h = x \]

the second order curvature

value for the distance of a curved target surface from the proximity sensor.

To compute the curvature of a surface and to compute a more accurate

2.4. Normal Curvature

in their measurement, and their distribution on the surface.

and orientation of a surface with the number of data points, the uncertainty

Equations (15) through (19) relate the uncertainty in the measured position

\[ \phi \leq \theta \]

The angle between the optical axis of the proximity sensor and the surface

\[ \theta \]

The curvature matrix for this case is

where \( f \) is the field of view and the intensity of the measured light, \( \phi \) is

where the uncertainty in the location of a light spot, \( \phi \) can be taken as a constant \( \phi \) for all of the data points.

\[ \begin{pmatrix} \phi \nabla \phi \nabla \psi \nabla \psi \nabla \psi \nabla \psi \nabla \psi \nabla \psi \end{pmatrix} \]

\[ \begin{pmatrix} \phi \nabla \phi \nabla \psi \nabla \psi \nabla \psi \nabla \psi \nabla \psi \nabla \psi \end{pmatrix} \]

Let us first examine the case of the plane
Figure 3: Measuring the Curvature of a Surface

light spots are shown as small circles on the surface. The intersection of the axis of the sensor with the target surface is located at P. The curve C on the surface is the intersection of the target surface with a plane (not shown) containing the axis of the sensor. The vector n is the principal normal of the curve C at P; it lies in the intersecting plane. The vector T is tangent to the surface, and to the curve C at P. The vector N is normal to the surface at P. The angle between the vectors n and N is $\phi$.

The equation of the fitted surface can be expressed as

$$R = \hat{x} \pm \hat{y} + (A_{x^2} + B_{z^2} + C_{y^2} + D_{z} + E_{x} + F_{y})k.$$  \hspace{1cm} (21)

The surface normal, N, is given by

$$N = \frac{R_x \times R_y}{|R_x \times R_y|} = \frac{(2A_{xz} + B_{zy} + D), -(Bz + 2Cy + E)}{\sqrt{(2A_{xz} + B_{zy} + D)^2 + (Bz + 2Cy + E)^2 + 1}},$$  \hspace{1cm} (22)

where the subscripts $x, y$ denote partial derivatives. The vector T, tangent to the surface, and to the curve C at P, is given by

$$T = \frac{dR}{ds},$$  \hspace{1cm} (23)

where $ds = |dR|$. The curvature vector $K$, whose magnitude is the curvature of C at P is then given by

$$K = \frac{dT}{ds}.$$  \hspace{1cm} (24)

The normal curvature vector, $K_N$, is the projection of K onto the surface normal N. The component of $K_N$ in the direction of N, $\kappa_N$, is called the normal curvature of C at P:

$$K_N = (K\cdot N)N = \kappa_N N.$$  \hspace{1cm} (25)

The magnitude of $K_N$ is the curvature of a curve on the surface, in the plane of N, with tangent vector T at P.

To compute the curvature of a surface, one first computes the first and second fundamental coefficients of the surface [10]. The first fundamental coefficients of the surface are
between N and n.

where \( N \) is computed in a direction tangent to \( C \) at \( p \) and is the angle

\[
\frac{D_{+} + 1^\wedge}{\theta^2 + D_{+} + 1^\wedge} = \frac{N_x}{N_y} = \tan \theta
\]

The principal curvature \( \kappa_x \) of the curve \( C \) at \( p \) is given by

\[
0 = \kappa_x - N_{x}^2 + \theta \tan (\kappa_x - N_{x}^2 + \theta) \quad (23 - N_{x}^2)
\]

The directions of the principal axes are given by the roots of the

\[
0 = \kappa_x - N_{x}^2 + \theta \tan (\kappa_x - N_{x}^2 + \theta)
\]
concave, light can be reflected about the surface. The center of gravity of the reflected light in the field of view will not coincide with the center of gravity of the projected light spot.

3.1. Distortion

To measure and then compensate for the distortion of the lens and the nonlinearity of the sensor, a uare array of light spots was generated in the field of view of the sensor. The coordinates output by the sensor were then compared with the results computed according to the geometrical model of the sensor. A two-dimensional transformation, \((x_c, y_c) \rightarrow (x_c', y_c')\), maps the measured sensor chip coordinates into their expected values [7]. This transformation is applied to measured sensor chip coordinates each time a light source is turned on when the proximity sensor is in use.

3.2. Light Source Trajectories

The sensor was used to measure the trajectories of the lights that are emitted from the sensor head. To do this, a flat surface was mounted perpendicular to the optical axis of the sensor head. The \(z\) coordinate of a spot of light on the surface is simply the \(z\) position of the surface. As each light source was turned on, the sensor chip coordinates were measured and the \(z\) and \(y\) coordinates of each light spot were computed. By moving the plane along the \(z\) axis of the sensor, a set of points \((z, y, z)\) for each light source was acquired.

For each light source, a line was fit through a subset of the acquired data point \((z, y, z)\), near the center of the field of view where \(z = 0\), and nonlinearity is small. These lines were used to estimate points of the light beam trajectories. The intersection of a line with the target plane \(y = 0\) is the coordinates of a set of points \((\bar{z}, \bar{y}, \bar{z})\). These points are considered to be the best estimates of points along the trajectory of a light beam.

3.3. Error Correction

Just as the set of points \((\bar{z}, \bar{y}, \bar{z})\) were computed, now a set of points \((z, y, z)\) are computed for each LED by triangulation. The error is taken to be the difference between the coordinates \((z, y, z)\) computed by triangulation and the coordinates \((\bar{z}, \bar{y}, \bar{z})\) computed according to the geometrical model.

Assuming that \((\bar{z}, \bar{y}, \bar{z})\) is the correct location of a light spot, let us set

\[
\bar{z} = z + \epsilon_z, \tag{37}
\]

\[
\bar{y} = y + \epsilon_y, \tag{38}
\]

\[
\bar{z} = z + \epsilon_z. \tag{39}
\]

It would be difficult to model the effect of the departures from the simplified model precisely to determine the terms \(\epsilon_z\), \(\epsilon_y\), and \(\epsilon_z\). However, since the errors are small and usually repeatable with respect to the measured spot position \((x_c, y_c)\) on the sensor chip, we model them as a whole by means of polynomials, for example, by third order correction polynomials of the form

\[
\epsilon_z = f(z, y) = a_{11}z^3 + a_{12}z^2y + a_{13}zy^2 + a_{14}y^3 + a_{15}z^2 + a_{16}zy + a_{17}y^2 + a_{18}z + a_{19}y + a_{20}
\]

where

\[
t = z, y, z.
\]

When the proximity sensor is calibrated, these polynomials are designed for each LED using a calibrated data set. During operation, the values
The $x$ coordinate of the spot of light on the sensor chip is

$$x_c = \frac{L}{z - L} x$$  \hspace{1cm} (42)$$

A small change in the $x$ coordinate of the target surface by $\Delta z$ corresponds to a shift in the spot of light on the sensor chip by $\Delta z_c$:

$$S = \frac{\Delta z_c}{\Delta z} = \frac{L}{(z - L) \tan \theta + (z - L)^2 \tan \theta}.$$  \hspace{1cm} (43)

The larger the magnitude of $S$, the more sensitive the measurement. The orientation of the light beam $\theta$ can be chosen so any measurement of distance using a single light source will have a nominal sensitivity $S_N$ in the center of the field of view, i.e., at $z = d$. This condition places an upper bound on the value of $\theta$:

$$\theta < \tan^{-1} \left( \frac{L}{(d - L) S_N} \right).$$  \hspace{1cm} (44)

Suppose one particular cone of light is generated using $n$ light sources equally spaced in a circle. When a flat surface intersects the cone of light beams normal to the axis of the cone, the spots of light fall on a circle. The radius $R$ of this circle is given by

$$R = |z - d| \cot \theta.$$  \hspace{1cm} (45)

To determine the uncertainty in the orientation of a plane that is fit to these points, the mean-square values of the coordinates are first calculated. For $n \geq 3$:

$$\sum_{i=1}^{n} x_i^2 = \frac{R^2}{n} \sum_{i=1}^{n} \cos^2 \frac{2\pi i}{n} = \frac{nR^2}{2},$$  \hspace{1cm} (46)

$$\sum_{i=1}^{n} y_i^2 = \frac{R^2}{n} \sum_{i=1}^{n} \sin^2 \frac{2\pi i}{n} = \frac{nR^2}{2}.$$  \hspace{1cm} (47)

Using Equations (16), (17), (18), and (19), the uncertainty in measured orientation when using a single cone of light can be calculated in terms of the uncertainty $\sigma$ in the measurement of spot position, the radius of the circle of points, and the number of light sources:

$$\sigma_\phi \leq \sigma \frac{R}{\sqrt{n}}.$$  \hspace{1cm} (48)

When using multiple cones of light, where the $j$th cone consists of $n_j$ light sources focused towards a point $d_j$ the radius of the $j$th cone at $z$ is

$$R_j = |z - d_j| \cot \theta_j.$$  \hspace{1cm} (49)

The mean square value of the $z$ coordinates of the data points is then

$$\sum_{i=1}^{n} z_i^2 = \frac{1}{2} \sum_j n_j \cot^2 \theta_j (z - d_j)^2.$$  \hspace{1cm} (50)

The uncertainty in measured orientation is

$$\sigma_\phi \leq \frac{2 \sigma}{\sqrt{\sum n_j \cot^2 \theta_j (z - d_j)^2}}.$$  \hspace{1cm} (51)

This equation guides the determination of the number of light sources $n_j$ in each cone, their orientation $\theta_j$, and their placement $d_j$. 
Resolution of the sensor chip is at least 1/500 the linear dimensions. This means, a signal-to-noise ratio can be achieved so that the effective position of the sensor, the light spot on a surface would then be further distinguished. We assume that when a light source is focused on a surface, the light spot on that surface would increase the sensitivity of the sensor, but the light spot on a surface would increase the sensitivity of the sensor. The goal is to increase the sensitivity of the sensor so that the light spot on a surface can be achieved. When a light source is focused on a surface, the light spot on that surface would increase the sensitivity of the sensor.

In order to achieve the desired sensitivity of the sensor, the light spot on a surface should be focused on a specific area of the sensor. To achieve this, a sensor with a focal length of 10 cm can be used. The focal length determines the area of the sensor that is sensitive to the light spot. The focal length should be at least 10 cm to ensure that the light spot is focused on the sensor.

In conclusion, the design of the proximity sensor is crucial to achieve the desired sensitivity. By focusing the light spot on a specific area of the sensor, the desired sensitivity can be achieved.
corresponds to $\Delta z_c = 0.026$ mm, and a shift in the position of the target surface by $\Delta z = 0.15$ mm. This value of $\Delta z$ is used to estimate $\sigma_z$. The total uncertainty $\sigma$ is estimated by observing $\text{Out}$ when the position of a point is calculated by triangulation, the solution is constrained to lie on the line determined by the light beam. Since $\sigma^2 \approx \sigma_z^2 + \sigma_y^2 + \sigma_x^2$, and $\tan 60^\circ = \sqrt{3}$,

$$\sigma_z^2 \approx 3(\sigma_y^2 + \sigma_x^2) \tag{52}$$

and therefore,

$$\sigma^2 \approx 1.33 \sigma_z^2. \tag{53}$$

The maximum value of the uncertainty in the measurement of surface orientation $\sigma_\phi$ occurs near the vertex of the middle cone. We use Equation (51) to calculate the minimum spacing between the vertices $d_1$, $d_2$, and $d_3$ of the cones of light by insisting the uncertainty in any single measurement of orientation at $z = d_2$ be less than $1.0^\circ$ (17.4 milliradians). Assuming these three cones are equally spaced, and consist of three light sources, we find

$$14.0 \text{ mm} \leq d_2 - d_1 = \beta_2 - \beta_1 \tag{54}$$

Figure 6 shows how the uncertainty in orientation $\sigma_\phi$ calculated by Equation (51) decreases as cones of light are added to the proximity sensor head. $\sigma_\phi(1)$ is graphed assuming a single cone of light consisting of three light sources is focused toward $d_2$. Then $\sigma_\phi(2)$ and $\sigma_\phi(3)$ are graphed as successive cones of light are added: first the cone with a vertex at $d_3$, then the cones with a vertex at $d_1$.

In order to further increase the accuracy of the sensor a second cone of light is focused at $d_1$ to augment the original light sources. In order to extend the range of the sensor, two more cones of light with an orientation of

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{These graphs display the uncertainty when measuring the orientation of a flat target surface. Curves 1, 2, and 3 show the uncertainty when using a single, then two, and then three cones of light, each having three light sources.}
\end{figure}

70° are focused towards points further along the optical axis. As a result, the range of the proximity sensor consists of two overlapping regions: first an inner region with a small field of view, a depth of 6 cm, and many redundant light sources where the sensor accurately measures the distance and shape of a surface, and then an outer region that extends the range of
The distance where the beam of light enters and leaves the field of view has been built into a metal block on the target surface, always within the optical field of the sensor. The distance between these two points, known as the distance to the target, is always maintained in the sensor's field of view. However, the location of the field of view is determined by the sensor's field of view, which is the area where the light source is visible to the sensor.

The measured distance to the target is the distance between the light source and the sensor. The sensor is mounted on the target, and the distance to the target is measured by the sensor. The sensor is a proximity sensor, which is used to measure the distance to the target.
C-mount lens can be mounted in front of the sensor chip. The light source is a screw into the flange of the barrel.

To summarize, the final parameters of the proximity sensor are:

- Camera lens focal length: \( f = 16 \text{ mm} \)
- Sensor chip to lens distance: \( L = 20.67 \text{ mm} \)
- Distance from sensor chip to plane in best focus: \( D = 91.4 \text{ mm} \)
- Orientation of inner rings of light sources: \( \theta_{1,2,3} = 60^\circ \)
- Orientation of outer rings light sources: \( \theta_{4,5} = 70^\circ \)
- Number of light sources in ring 1: \( n_1 = 6 \)
- Number of light sources in outer four rings: \( n_{2,3,4,5} = 3 \)
- Distance between inner light source target points along the optical axis: 15.24 mm

This particular sensor head weighs approximately one pound. Future versions of the sensor can be constructed of composite materials to reduce the sensor's weight.

5. Performance

5.1. Measuring Distance and Orientation

The proximity sensor was used to measure the distance and orientation of flat target surfaces to determine the accuracy of the sensor. The target surfaces were moved by high-precision linear and rotary platforms in the field of view of the sensor. Each surface was rotated in 2° increments from \(-15^\circ\) to \(+15^\circ\), and moved in 2 mm steps in front of the sensor. The distance and orientation of the surfaces were measured and compared with their expected values.

The results for a uniform white target are summarized in Figures 8 and 9. The graphs show the error in measured distance as a function of the actual distance and orientation of the surface. The error in orientation is typically less than 2°, while the error in the measurement of distance is less than 0.2 mm.

The amplifier gains of the proximity sensor were set so that the sensor could measure the distance of a matte surface over a range of 10 cm. The light intensity measured by the sensor agreed with the expected result when the white surface was used as a target. However, the reflectivity of an unpainted aluminum surface, for example, is less than that of a white surface, and in addition the reflected light has a large specular component. As a result, the range of the sensor was limited to 5 cm when measuring the distance of this type of surface. Either an insufficient amount of light is scattered by the surface towards the sensor, or alternatively, light is specularly reflected directly towards the sensor and overflows the amplifiers.

The measured coordinates of a light spot on a target surface also has a
larger surface were computed for each position of the surface. The distance
expected results. The coordinates of the resultant height spots on a simulated

The measurement of surface shape was simulated to evaluate the
surface that was computed assuming the proximity sensor behaved ideally.
The results were compared with the actual shape of each surface and with shape of each
orientation and curvature of the reference surface were computed. The results were

To measure the contour of a surface, a surface was moved through the

Figure 10: Aluminum surface error in measured ellipse versus

orientation and distance after recalibrating the sensor.

Figure 11: While surface error in measured orientation versus

distance in mm (0) 10.64 mm (50) 1.0 mm step
Figure 1: Aluminum surface: error in measured rotation versus orientation and distance after recalibrating the sensor.

Since measuring the contour of a surface uses only a small range of the range of the sensor, relative measurement errors are generally small. For example, when a flat surface with uniform reflectivity was moved across the field of view of the sensor, the error in measured distance was much less than the errors that were reported when the distance and orientation of the surface were varied over a range of 10 cm. In many applications of the proximity sensor, a target surface will be nearly flat. In addition, the sensor can be moved to maintain a fixed distance and orientation above a target surface to achieve a better measurement.

The shapes of a cylinder and a cone were measured by moving each surface linearly across the field of view of the sensor a distance of 5 cm in 2 mm steps. The cylinder was in focus when closest to the sensor; the cone was positioned 6 mm further away. Both the cylinder and the cone were covered with a sheet of matte white paper. The cylinder had a 57.15 mm (2.25 inch) radius. In Figure 14 the contour of the cylinder is graphed as the sensor was moved across its surface.

The cone that was used as a target had a base angle of 81°. At the height at which the axis of the sensor intersected the surface of the cone, the cone
The data points in Figure 16 and 17 show the measurement results and the
orientation of the target surfaces in a cylindrical surface when the surface
measure test and orientation is modeled. Surface data show that the proximity
sensor can accurately

For example, the data in Figure 17 shows the

actual contour of the sensors.

When the orientation of each of

the contour lines is drawn with the actual values,

Figure 14: Contour of the surface of a cylinder: the measured values and

the simulation results, along with the actual values

![Graph of contour lines](image1)

<table>
<thead>
<tr>
<th>Orientation (°)</th>
<th>Measured Distance (mm)</th>
<th>Measured Orientation Error (°)</th>
<th>Modeled Distance (mm)</th>
<th>Modeled Orientation Error (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>135</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>180</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 13: Measured surface error in measured orientation versus
distance.
Figure 15: Contour of the surface of a cone: the measured 1 and the simulated 2 results, along with the actual 3 values.

The principal normal curvatures, $\kappa_1$ and $\kappa_2$, of the cylinder and the cone were also computed. Figures 18 and 19 respectively show the smaller value for the computed principal radius of curvature of the cylinder and of the cone. The curves labeled '1' are the measured results and the curves labeled '2' show the simulation results. The solution for the curvature of the cylinder and the cone can be chosen where the other principal radius of curvature has a maximum. For the cylinder this occurs where $z = -6$. For the cone this occurs where $z = 2$.

The proximity sensor can accurately measure the distance and orientation of a smooth surface when maintained at a near normal position relative to the surface. According to the simulation results, the proximity sensor has the potential to accurately measure the curvature of a surface.

Figure 16: Surface orientation of the cylinder: measured 1 and simulated 2 results, and the actual value 3. The orientation is measured with respect to the axis of the proximity sensor.
The proximity sensor that has been built on a surface are calculated. The proximity sensor is based on the principle of active illumination and translation. The sensor is used in the field of machine vision and industrial automation.

A new compact multi-light source proximity sensor has been developed.

6. Conclusion

The accuracy of the proximity sensor measured for the light sources and the actual value is calculated using the principle of active illumination and translation. The simulation model of the sensor was built and tested. The sensor is suitable for use in a range of applications.

Figure 1: Surface orientation of the cone measured 1 and 2.

Figure 2: Surface orientation of the cone measured 1 and 2.
within a specified accuracy to the distribution of light spots on a target surface. The new design is also intended to be a compact sensor for use on a robotic manipulator.

The proximity sensor is subject to error because of various types of distortion, nonlinearity, and noise. To compensate for the distortion of the sensor chip and imaging optics, a square array of light spots was generated in the field of view. A two dimensional transform was computed that maps the measured image of this array on the sensor chip into its ideal undistorted image. This transform was applied to the sensor chip coordinates during the operation of the sensor.

To further compensate for errors in the computation of distance, error correcting polynomials were computed that map the distance of a surface computed by triangulation into its actual distance. These polynomials were used during the operation of the sensor to improve measurement results.

The features of this proximity sensor include its simple principle of operation and its fast speed. The sensor chip which detects the spot of light on the target surface is an analog device which outputs the position of the centroid of a spot of light on its surface. Although the accuracy of any individual measurement of light spot position is limited by the distortion of a spot of light by a surface, and the noise and sensitivity of the sensor, we take advantage of the speed of the sensor and use multiple light sources to increase the overall accuracy of measurements. The geometrical arrangement of the light sources was guided by the statistical analysis to achieve the design specification for accuracy. Measurement of distance, surface orientation and surface curvature can exploit the geometrical redundancy of the device.

Acknowledgments

We thank Regis Hoffman and Donald Schmits for useful discussions and help in software and hardware development. This research was partially supported by the Office of Naval Research (ONR) Grant No. N00014-81-K-0503, and by the National Science Foundation Grant No. ECS-8320364.