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INTRODUCTION

Recently, a great deal of interest has been shown in making accurate range measurements with good transverse definition. This capability makes it possible, in machine vision systems, to extract geometrical shape information from the images. In robot position sensing, it is important to determine the absolute distance instead of distance change so that noncontinuous measurements can be made without the need for calibration at start-up. A third application of great importance is to measure the shape and size of machined parts with a noncontacting sensor.

Research in the area of distance measurements has been carried out for many years using several different techniques. One technique is to use interferometry, which requires a high-quality laser. The method yields excellent range accuracy, but suffers from phase wraparound; thus, without additional complexity, such as the use of two laser frequencies or the employment of extremely high-frequency modulation, it is not possible to make noncontinuous distance measurements. An alternative technique is to use a triangulation; this method does not usually provide very good transverse resolution and is attractive only when the accuracy requirement is on the order of 100 μm or greater.

In this paper, we describe a new optical technique which is based upon the type II microscope. With this system, we have made absolute distance measurements with a range accuracy of 2 μm and a transverse definition of 10 μm at a working distance of 15 cm. The system is stable, easy to align, and largely insensitive to the tilt and roughness of the object.

THEORY AND EXPERIMENTAL SET-UP

A schematic diagram of the optical range finder is shown in Fig. 1. The objective lens focuses the laser beam to a spot of the order of 5 μm diameter, so that most of the beam passes through a 10 μm diameter pinhole. A camera lens placed beyond the pinhole focuses the
light onto a point on the object. An image of this point is, in turn, focused on the pinhole. The reflected light passes back through the pinhole and is detected by the photodetector. When the object is located exactly at the focus of the transmitted light, the maximum amount of light passes through the pinhole. Otherwise, when the system is partially defocused, the amount of light passing through the pinhole is reduced. We therefore expect the signal output from the detector to have a strong dependence on the position of the object.

Because a focused beam is employed and the phase changes between the different rays comprising the beam are very small, the phase fluctuations of the laser are unimportant; therefore, a semiconductor laser, or even an incoherent source, can be used. Furthermore, the employment of a focused beam implies that the transverse definition of the system is excellent.

It will be noted that the system shown is deceptively simple. In confocal scanning microscopy, it is common to employ two pinholes so as to eliminate the reflected light from the transmitting pinhole, or to use a collimated input beam to the objective lens instead of a pinhole. In both cases, the light passes through the pinhole only once. The optical alignment procedure required for an optical range finder, which has a much longer working distance than the microscope, is extremely difficult with such a two-pinhole system. Thus, our system uses the single pinhole technique in which the light beam passes through the pinhole twice. It is easy to align and very stable. In this case, the light reflected back from the 10 μm pinhole is eliminated by focusing the beam to a spot size of 5-6 μm.

We assume a lens with a pupil function \( P(\theta) \) where \( \theta \) is the angle between the ray from the pupil plane to the focal point and the axis. By following the derivation of Richards and Wolf for vector fields, with some minor changes, it can be shown that the transverse electric field associated with a plane wave focused by the lens to a point on axis a distance \( z \) beyond the focal plane is of the form

\[
D(z) = \int_{0}^{\theta_0} \frac{(1 + \cos \theta) \sin \theta}{(\cos \theta)^{1/2}} e^{jkz \cos \theta} P(\theta) d\theta
\]  

(1)

It will be noted that there is a \((\cos \theta)^{1/2}\) term in the denominator rather than in the numerator, as it is in Wolf's theory, in order to conserve power at a flat exit plane from the lens.
The integrand of Eq. (1) expresses the amplitude and phase of the plane wave components of the E field at an angle $\theta$ to the axis. When a focused beam is reflected from a plane mirror, its image will be a distance $2z$ away from the focus. In our apparatus, the reflected image is refocused onto the pinhole in front of the detector. Thus, it is the field on axis at the focal plane of the objective lens which is imaged at the pinhole. This field is of the form

$$V(z) = \int_{0}^{\theta_0} \frac{(1 + \cos \theta) \sin \theta}{(\cos \theta)^{1/2}} e^{2jkz \cos \theta_0} R(\theta) d\theta$$  \hspace{1cm} (2)

where the output signal from the detector is proportional to

$$I(z) = |V(z)|^2$$  \hspace{1cm} (3)

In these expressions, $R(\theta)$ is the reflection coefficient of the plane reflector, $k$ is the wave number $(2\pi/\lambda)$, $f$ is the focal length of the lens, and $\sin \theta_0$ is its numerical aperture, where $\sin \theta_0 = a/f$, and the radius of the lens is $a$. With uniform excitation, $|P(\theta) = 1$ for $\theta < \theta_0|$, $ka \gg 100$, and a plane reflector $[R(\theta) = 1]$. An approximate expression for $|V(z)|$ has been derived by Liang et al.

$$|V(z)| = \left| \frac{\sin kz(1 - \cos \theta_0)}{kz(1 - \cos \theta_0)} \right|$$  \hspace{1cm} (4)

This expression accurately predicts the shape of the central lobe; however, it fails to account for asymmetries in the sidelobes. The depth of focus is given by the 3 dB points of the central lobe in Eq. (4).

$$(\Delta z)_3 \, dB = \frac{0.443 \lambda}{1 - \cos \theta_0}$$  \hspace{1cm} (5)

For small $\theta_0$, the numerical aperture (N.A.) of the lens is given by the relation [N.A. = $\sin (\theta_0) = \theta_0$]. With $\cos \theta_0 = 1 - \theta_0^2/2$, we can write Eq. (5) in the form

$$(\Delta z)_3 \, dB = \frac{0.886 \lambda}{(\text{N.A.})^2}$$  \hspace{1cm} (6)

We used a 4 mW He-Ne laser with a wavelength of 6328 Å in these experiments. A semiconductor laser could have been employed equally well; we chose to work with the gas laser initially only because of its availability and the greater ease of working with visible light in the early experiments. We found it convenient to use a Bragg cell for amplitude modulation of the incident light; with a semiconductor laser, we could directly modulate the laser itself. Since the objective lens is not specially coated for the He-Ne wavelength, there is still some light reflected back from the objective lens. To reduce the amount of the reflected light reaching the detector, we simply place an iris diaphragm.
before the photodetector. An iris diaphragm placed between the pinhole and the objective lens reduced the numerical aperture of the reflected light. This increased the spot size of the returning one-way spatial filter. The object was moved by two actuators in the axial direction \( z \) and the transverse direction \( x \). The whole system was controlled by a computer.

RESULTS

To demonstrate the usefulness of this system for obtaining accurate distance measurements, we used a mirror as the reflecting object and scanned it in the axial direction \( z \). Figure 2 shows the dependence of the signal on the position of the object. The numerical aperture of the optical system is \( 0.054 \), the corresponding depth of focus is \( 188 \, \mu \text{m} \), and the spot size is about \( 10 \, \mu \text{m} \). The experimental curve fits the theoretical curve very well, except for some discrepancy in the side-lobes, which is believed to be caused by aberrations in the optical system. By determining the position of the peak of the curve, we can determine the position of the object very accurately.

Fig. 2. The dependence of the detected signal amplitude on object distance for a mirrored surface.

Fig. 3. One-dimensional scan over a tilted mirror.
To determine the sensitivity of our measurement technique, we scanned the focused beam over a tilted mirror, as shown in Fig. 3. The straight line represents the mirrored surface and the dots are experimental results. The estimated accuracy is about 2 μm. As we tilted the mirror, the height of the central lobe decreased and the depth of focus increased. This is because less light could be collected by the camera lens, so the effective numerical aperture decreased.

The results of a subsequent scan over a 220 μm step on a specular reflector are shown in Fig. 4. The transverse spacing between adjacent points is 5 μm. Except for the overshoot near the step, the accuracy of the range measurement is about 2 μm. The overshoot is due to shadowing and interference effects which are illustrated in Fig. 5. The focused light is reflected by both top and bottom surfaces. Most of the light reflected from the bottom surface is blocked by the step, except that reflected back at a small angle. The interference between the two beams shifts the center peak and causes the overshoot effect.

This system is not only suitable for measurements on smooth surfaces, but also for measurements on rough surfaces. This is because when the light is focused to a point on a rough surface, the reflected light will be scattered in all directions, but an image of this point

Fig. 5. Illustration of shadowing and interference effects.
can still be obtained at the pinhole. We pay a price for this convenient result — the light reaching the pinhole is much reduced in intensity; the advantage is that the alignment of the rough surface is relatively uncritical. To demonstrate this effect, we scanned a sample of sheet aluminum over the surface, as supplied by the manufacturer. The results we obtained are shown in Fig. 6. The central lobe of this curve is unchanged from the central lobe obtained using a mirror. As expected, the detected signal from this rough surface is much weaker than that for a smoother surface, but it is still strong enough to be easily detected with a narrowband receiving system. The results obtained were insensitive to the tilt of the object, which is essential for the measurement of ordinary machined parts.

CONCLUSIONS

We have demonstrated an optical range finder with a range accuracy of 2 μm and a transverse definition of 10 μm at a working distance of 15 cm. The device, based upon the type II microscope principle, is very stable, easy to align, and suitable for measurement over both smooth and rough surfaces.

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