Coarse error analysis and correction of a two-dimensional triangulation range finder

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Received September 19, 2005

A real-time two-dimensional (2D) triangulation range finder is presented, which is composed of two linear complementary metal oxidation semiconductor (CMOS) chips, two camera lenses, and four light emitting diodes (LEDs). The high order distortion in image aberrations is the main factor responsible for the coarse errors. The theoretical prediction is in good agreement with experiments and the correction equation is used to obtain more reliable results with the unique distortion coefficient in the whole working region.

OCIS codes: 120.0120, 150.5670, 220.1000, 280.0280.

It is well known that the triangulation method has been widely used in many applications[1−7] owing to its significant advantages in simplicity and robustness. A conventional optical triangulation sensor usually measures the absolute positions of an object in longitudinal direction. Zeng *et al.* have realized the two-dimensional (2D) position measurement by using a two-beam laser triangulation method[5]. But the configuration is also become more complicated due to splitting the laser beams. In addition, many triangulation range finders adopt laser diode and charge-coupled device (CCD) camera, which greatly enhance the cost of the sensor. In order to realize a simple, low cost real-time 2D position measurement, we developed a range finder by using linear complementary metal oxidation semiconductor (CMOS) chips and light emitting diodes (LEDs). The coarse error of this system is discussed in detail.

The configuration of the 2D triangulation range finder is shown in Fig. 1. Four LEDs with a wavelength of 650 nm and output power of 5 mW are used to illuminate the moving object. The object is imaged by two lenses 1 and 2, respectively. The positions of the image centers A and B are measured by two linear CMOSs (Panavision SVI, RPLIS-2048). According to clock time, the electronics reads out the sensing elements at the same time from CMOS 1 and 2. If the length of sensing elements is smaller than 10 pixels, the signal is cast aside used as noise. The axes of x and y, the zero point $O(0,0)$ and the target point $P(x,y)$ are shown in Fig. 1. Two axes of lenses are x' and x'', which are parallel to each other. The viewing line from the image center A on CMOS 1

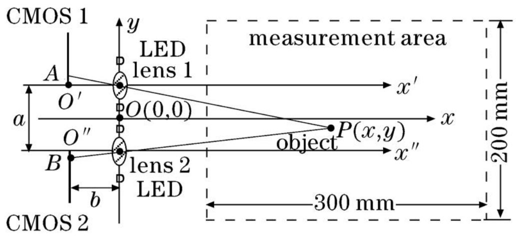

Fig. 1. Configuration of the 2D triangulation range finder.

through the center of lens 1 can be used to determine the azimuth of object $P(x,y)$ with respect to axis x'. The CMOS 2 and lens 2 give another viewing line. The two viewing lines have a cross, at which the object is just located. Then the target position $P(x,y)$ can be simply expressed as

$$x = \frac{ab}{h_1 - h_2}, \tag{1}$$

$$y = \frac{a}{2} - \frac{ah_1}{h_1 - h_2}, \tag{2}$$

where h_1 and h_2 represent the distances from the image centers A and B to the corresponding centers of CMOSs. When the image points are above or below each axis, h_1 and h_2 are defined as positive or negative, respectively; the parameter a is the distance between two lenses' axes; b is the distance from lens to linear CMOS. Parameters a and b are both accurately set, and then the object position can be calculated.

In the experiment, a = 35 mm and b = 5 mm. The focal length of the lenses is 3.3 mm. Measurement errors Δx and Δy can be calculated by subtracting calibrating values from experimental values obtained by Eqs. (1) and (2), respectively. Figures 2 and 3 show the measurement

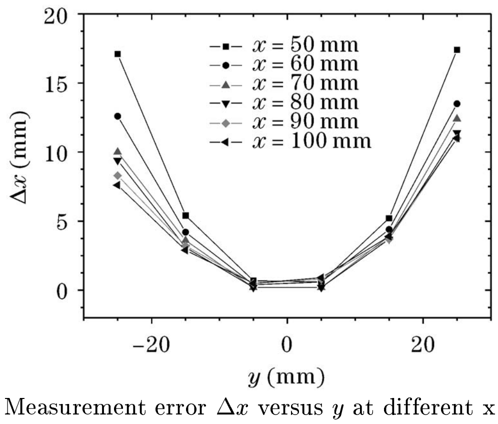

Fig. 2. Measurement error Δx versus y at different x coordinates.

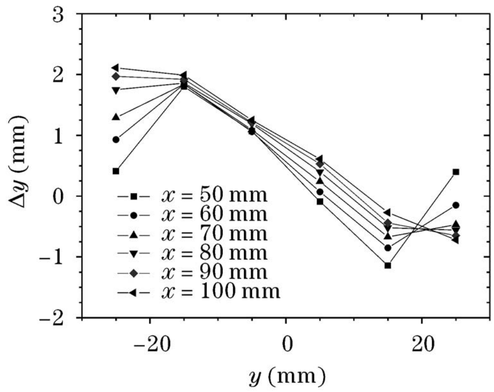

Fig. 3. Measurement error Δy versus y at different x coordinates.

errors Δx and Δy versus y at different x coordinates, respectively. It can be seen that the measured values have bigger differences from actual values, especially for the measurement error Δx. Obviously, the measurement results of x are unpractical. But these coarse errors have some regular distributions. Δx and Δy have shown that the coarse errors are symmetric, and the curves of Δx versus y are parabolic in shape. It is necessary to find the error source of x and correct it effectively.

There are many effects possible to bring coarse errors, such as vignetting effect and optical aberrations. In this triangulation range finder, the distances among single lens in compound camera lens are very short and the compound lens has been optimized by manufacture for practical application. So the vignetting effect does not change the image centers on both CMOSs in the working region, i.e., it does not contribute to the coarse errors. Moreover, many aberrations such as spherical aberration, chromatic aberration, coma, astigmatism and curvature of field are axially symmetric, so all of these aberrations do not change the center of project image on CMOS in this 2D triangulation range finder. The distortion in aberrations has the possibility to produce additional error because of asymmetric characteristic. The primary distortion of camera lens has been corrected to the allowable degree, so the high order distortion should be discussed in detail.

In the high order distortion, the wave distortion is expressed as

$$\varphi \propto y_0^5 \rho \cos\theta, \tag{3}$$

where y_0 is object height, ρ is the radius at aperture of lens, θ is the angle of principal ray to optical axis[8]. The corresponding geometric aberration is

$$\Delta y_0 \propto \frac{\partial \varphi}{\partial y_0}. \tag{4}$$

Therefore, the project height of principal ray Δy_0 on CMOS is proportional to y_0^4, that is, to $\mathrm{tg}^4\theta$, here θ is the angle of principal ray to axis. Equations (1) and (2) are modified as introducing distortion of lens

$$h_1 + \alpha b \mathrm{tg}^4\theta_1 = b\mathrm{tg}\theta_1, \tag{5}$$

$$h_2 - \alpha b \mathrm{tg}^4\theta_2 = -b\mathrm{tg}\theta_2, \tag{6}$$

where θ_1 and θ_2 are the angles of principal rays to optical axes x' and x'' respectively, with $\theta_1 = (a/2 - y)/x$ and $\theta_2 = (a/2 + y)/x$; α is the distortion coefficient. Then, the actual value of x with high order distortion can be deduced as

$$x = ab/(h_1 - h_2)\{1 + [\alpha b(\mathrm{tg}^4\theta_1 + \mathrm{tg}^4\theta_2)]/(h_1 - h_2)\}. \tag{7}$$

The distortion coefficient α can be deduced from Eq. (7) as

$$\alpha = a x_e^3 [x_e/(x-1)]/[(a/2 - y_e)^4 + (a/2 + y_e)^4], \tag{8}$$

where x_e and y_e are the measured values in the experiment from Eqs. (1) and (2). The bigger the y_e, the larger the difference between $(a/2-y_e)^4/x_e^4$ and $(a/2+y_e)^4/x_e^4$ with the actual values of $\mathrm{tg}^4\theta_1$ and $\mathrm{tg}^4\theta_2$ respectively. So the values of α must change with y_e. Based on Eq. (8), α can be expressed as

$$\alpha = C_0 + C_1 y_e^2 + C_2 y_e^4, \tag{9}$$

here $C_0 = 4.89 \times 10^{-2}$, $C_1 = 4.78 \times 10^{-3}$ and $C_2 = -5.37 \times 10^{-6}$ are obtained approximately by the least squares method as selecting a set of measured values (x = 70 mm). Consequently, the measured values after correction can be described as

$$x = a x_e^4 / \{a x_e^3 + [(a/2 - y_e)^4 + (a/2 + y_e)^4] \times (4.89 \times 10^{-2} + 4.78 \times 10^{-3} y_e^2 - 5.37 \times 10^{-6} y_e^4)\}. \tag{10}$$

Figure 4 shows the measurement error of x after correction versus y at different x coordinates. Compared with the primary results in Fig. 2, it is found that the measurement error after correction is greatly decreased from the average value of Δx of 4.93 mm to 0.11 mm. Especially, the measurement error Δx is no longer very large when the absolute values of y are in a large level. So these results after correction become reliable and can be adopted in many applications. In addition, there exist some fewer measurement errors by using the above correction

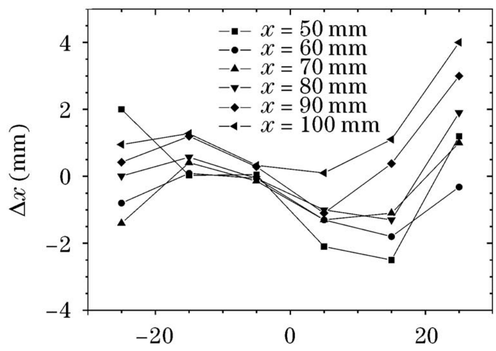

Fig. 4. Measurement error Δx after correction versus y at different x coordinates.

equations. We think the main reason is that some other factors also bring smaller errors. The measured results can be corrected by the experience equation further if necessary.

In summary, we demonstrated a simple real-time 2D triangulation range finder by using linear CMOSs and LEDs. It is found that the major measurement error results from the high order distortion in image aberrations. The measurement error Δx is greatly decreased from the average value of 4.93 mm to 0.11 mm after the experimental results are corrected. This range finder has large measurable range and is suitable for tracking many kinds of moving objects with different diffusing characteristics becauses of using active LED illumination. After correction, this type of triangulation range finder can be used in many applications.

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