A robust signal processing algorithm for linear displacement measuring optical transmission sensors

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Optical triangulation sensors fall into a general category of noncontact height or displacement measurement devices and are widely used for their simple structure, high resolution, and long operating range. However, there are several factors that must be taken into account in order to obtain high accuracy and reliability: Measurement errors from inclinations of an object surface, probe signal fluctuations generated by speckle effects, power variation of a light source, electronic noises, and so on. In this article, we propose a signal processing algorithm, named expanded average square difference function (EASDF), for a newly designed optical triangulation sensor which is composed of an incoherent source, a line scan array detector, a specially selected diffuse reflecting surface, and several optical components. The EASDF, which is a modified correlation function, can calculate displacement between the probe and the object surface effectively even if there are inclinations, power fluctuations, and noises. This optical triangulation sensor system with the EASDF shows an 8 mm linear operation range and 1 μm resolution without averaging and the maximum measurement error is 2.4 μm for ±10° inclinations. © 2000 American Institute of Physics.

I. INTRODUCTION

Optical triangulation sensors have been widely used in industrial measurement applications because they utilize the advantage of noncontact measurement with the ability to measure submicron resolution. Moreover, they have fast response, a simple structure, good repeatability, high sensitivity, and a relatively long operating range. However, a large amount of error originating from an inclination of an object surface, speckle effects, optical power fluctuations of light sources, and noises in detectors limits the usability of optical triangulation sensors.4–6

Figure 1 shows the measurement principles of optical triangulation sensors. They convert the change of a spot position on the detector into object displacement on the assumption of perfect spot point. However, actually, there is a light intensity distribution (LID) on the detector. Various factors such as inclinations of the object surface, speckle effects, optical power fluctuations of the light source, and noises in the detector change properties of the LID. Therefore, the LID on the detector should be seriously considered in order to get accurate and precise measurement.

Many studies have attempted to reduce these errors. One proposed solution was to arrange several sensors around the object surface to get more accurate output through spatial averaging.7,8 However, it is not easy to make a compact sensor structure and fast enough signal processing algorithm. Another approach was to design optical triangulation sensors that can process not only a spot position change but also the total amount of light intensity on the detector.9 However, the idea is not adequate for actual applications due to the total amount of light intensity being very sensitive to light source power variation and noises. This article proposes an accuracy enhancement technique for optical triangulation sensors. For this purpose, we designed a system structure that can minimize the errors of optical triangulation sensors. Detailed review and investigation of the structure is presented in Sec. II. The characteristics of the LID on the detector are investigated through simulations and experiments in Sec. III. Signal processing algorithms are the key factors for estimating displacement from the LID on the detector. A signal processing algorithm, named expanded average square difference function (EASDF) for the proposed optical triangulation sensor structure is given in Sec. IV. Finally, we conclude this research in Sec. V.

II. ERROR MINIMIZING SYSTEM STRUCTURE

Among various parameters that can define the properties of the LID on the detector, only a peak position of the LID can represent the displacement of the object exactly. Other parameters of the LID such as the maximum value and an offset level are very sensitive to various error sources. Thus, the detector of optical triangulation sensors must find the peak position of the LID on itself. Of many types of optical detectors available, two are most commonly used for optical triangulation sensors: Position sensitive devices (PSDs) and charge-coupled devices (CCDs). CCDs can obtain the entire spatial distribution while PSDs, the widely accepted detectors for optical triangulation sensors, can get only the centroid position of the LID. If the LID on the detector has a symmetric shape, the peak position coincides with the centroid position. But due to Scheimpflug’s condition and lens aberrations, this hypothesis is not efficacious. For this rea-
son, PSDs cannot guarantee accurate measurement although they have unlimited resolution and fast time response.

Another critical effect on the LID is subjective speckle that arises from coherent light scattering off a rough surface. To eliminate this, we propose to replace the laser source with an incoherent source like a light emitting diode (LED). Also, reflection characteristics of the object surface have an influence on the LID. Since the characteristics of the surface can be determined through experiment only, i.e., they are not predictable, no triangulation sensors are able to measure the object displacement no matter what the object surface conditions are. The only way of guaranteeing accurate and precise measurement is to attach a patch on the object surface. We suggest white drawing paper, a diffuse scattering surface, as the patch. White drawing paper is popular and its physical effect on the object is extremely small because its thickness and mass per area are $80 \, \mu m$ and $6.4 \, mg/cm^2$, respectively.

### III. INVESTIGATIONS OF THE LID

In order to investigate the shape of the LID and the validity of the proposed optical triangulation sensor system, computer simulations and experiments have been carried out. Smith developed a simulation model for optical triangulation sensors using simple ray tracing and the principle of superposition.\(^{10}\) In Smith’s model, the light source, reflection surface, and ray propagation mechanism of the model were simplified too much. Consequently, the simulation results did not adequately reflect the real situation. In this study, we suggest a new model of optical triangulation sensors (Fig. 2).\(^{11}\) The incoherent light emitted from a source is divided into \(m\) light elements on the focusing lens (Fig. 2) using a polar coordinate \((r,\sigma)\). The light intensity profile on the focusing lens is assumed to be Gaussian. The majority of the \(m\) light elements are concentrated very near to the center of the focusing lens, because the intensity of the emitted light decays exponentially in a radial direction.

It is assumed that one of the \(m\) light elements from the focusing lens propagates straight toward the focus and after passing through the finite-area focus, it changes the propagation direction as Fig. 3 shows. We also postulate that it is reflected diffusely on the object surface, that is, it propagates in all the directions after being reflected. The light intensity on the \(i\)th pixel of the array detector by one of the \(m\) light elements, \(i(r,\sigma)\), whose polar coordinate value on the focus lens is \((r,\sigma)\) can be expressed as Eq. (1):

\[
i(r,\sigma) = kI_{in} \exp \left(-\frac{2r^2}{4R^2}\right) \Omega \cos \eta \frac{d}{d^2},
\]

where \(k\), \(I_{in}\), and \(R\) denote the proportional constant, input optical power of the light source, and radius of the beam spot on the focusing lens plane, respectively. In Eq. (1), it is hypothesized that the light intensity on the \(i\)th pixel is directly proportional to the light intensity on the part of the image lens, \(i_a-i_b\), in Fig. 2. Also, the light intensity on \(i_a-i_b\) is regarded as being inversely proportional to the square of the distance \(d\), between the center of \(i_a-i_b\) and the object surface, and being proportional to \(\Omega\) and \(\cos \eta\). The \(\eta\) is the angle between the normal vector of \(i_a-i_b\) and the line which represents diffusely reflected rays incident to \(i_a-i_b\). Using the principle of superposition, the light intensity on the \(i\)th pixel \(I_i\) can be given as

\[
I_i = \sum_{a} \sum_{b} \frac{kI_{in}}{d^2} \exp \left(-\frac{2r^2}{4R^2}\right) \Omega \cos \eta \cos \theta.
\]
\[ I[i] = \sum_r \sum_\sigma i(r, \sigma) \]
\[ = \sum_r \sum_\sigma kI_m \exp \left( -\frac{2r^2}{4R^2} \Omega \cos \eta d^2 \right). \]  \hspace{1cm} (2)

Simulation results are shown in Fig. 4. Simulation parameters are as follows: \(a = 35.0 \text{ mm}, \ b = 48.1 \text{ mm}, \ L_{\text{focus}} = 38.1 \text{ mm}, \ w_0 = 5 \mu\text{m}, \ \theta = 30^\circ, \ \phi = 22.8^\circ, \ \text{and} \ \varphi = 1.72^\circ. \) The detector is assumed to have 1024 (12 \( \mu\text{m} \) ) pixels. The left figure shows the LID for various object displacements. The results reveal that the maximum level and peak positions of the LID vary with displacement change and the shapes of the LID are asymmetric. If the offset level of the distribution fluctuates, the centroid values of the LID also change because the shape is not symmetric. The right figure shows that the peak positions of the distribution remain constant although maximum values alter with the angle \( \beta \) for fixed displacement. Therefore, in order to design optical triangulation sensors that are robust against errors, peak positions of the LID must be detected and converted into object displacement.

Figure 5 represents experimental results for various \( \beta \) and fixed \( \alpha \). Experimental parameters are as follows: \(a = 65.9 \text{ mm}, \ b = 46.3 \text{ mm}, \ L_{\text{focus}} = 38.1 \text{ mm}, \ w_0 = 12.5 \mu\text{m}, \ \theta = 48^\circ, \ \phi = 42^\circ, \ \varphi = 2.0^\circ, \ \text{and} \ 12 \mu\text{m} 1024 \) pixels array detector. As the surface becomes more distant from the probe head, the peak position of the LID shifts to the right direction on the pixel of the detector and the maximum value of the LID grows larger. The peak position of the LID remains constant if the relative displacement is fixed while the maximum values of the LID vary with inclination changes. The tendencies of the LID shown in Fig. 5 are consistent with the simulation results. Figure 5 also shows that the relationship between the peak position and the displacement is almost linear and robust against the inclination change. However, if the centroid position of the LID is used to calculate the object displacement, the relationship between sensor output and
actual displacement would vary with the inclination angle $\beta$ because of the asymmetry of the LID. Also, the asymmetry of the LID causes changes of the centroid values with variations of the ambient light level or the power of the light source even if the displacements remain constant as Figs. 6 and 7 show.

### IV. SIGNAL PROCESSING ALGORITHM

A signal-plus-noise sequence of the LID on the detector can be mathematically modeled referring to the experimental results as follows:

$$s_1[n] = x[n] + k_1[n] + \text{Offset}_1,$$

(3)

---

**FIG. 6.** Experimental results—the LIDs on the detector as background noise level changes and converted displacements with the centroid detection algorithm (Level 0=no noise, Level 1=10 uW optical noise, Level 2=20 uW optical noise).

**FIG. 7.** Experimental results—the LIDs on the detector as input optical power changes and converted displacements with the centroid detection algorithm (pow1=10 uW input, pow2=15 uW input, pow3=20 uW input).
where $n$ is a pixel number (for example, $1 \sim 1024$), $k_1[n]$ is Gaussian white noise, and Offset$_1$ represents an offset of the sequence. $x[n]$ represent the theoretical LID. After one sampling period, the sequence of the LID can be expressed as

$$s_2[n] = \alpha_{\text{att}} x[n - \Delta] + k_2[n] + \text{Offset}_2,$$

where $\Delta$ represents the movement of the peak position of the LID, which is proportional to the displacement, and $\alpha_{\text{att}}$ is an attenuation coefficient, which reflects the peak level change to acquire uncorrelated. The goal of the signal processing algorithm is to estimate $\Delta$ from two sequences with various $\alpha_{\text{att}}$. The previous sequence $s_1[n]$ is stored into a memory of the signal processing unit. The noise terms $k_1[n]$ and $k_2[n]$ are assumed to be mutually uncorrelated. The goal of the signal processing algorithm is to acquire $\Delta$ from two sequences $s_1[n]$ and $s_2[n]$ even if there are the attenuation factor $\alpha_{\text{att}}$ and noises. The resolution of CCDs is limited to the pixel size. To overcome the problem of limited resolution in CCDs, the algorithm must detect $\Delta$ in subpixel resolution. In addition, the algorithm must be fast enough for a real-time implementation.

Many subpixel resolution detection schemes that can estimate $\Delta$ from two sequences have been proposed over many years. The most commonly used schemes can be categorized as the interpolation method and correlation method. However, interpolation not only increases the complexity and data flow of the coder but also affects the accuracy of the estimation because of a poor signal-to-noise ratio. Meanwhile, correlation techniques have advantages over interpolation techniques such as robustness against noises and simple real-time implementation with the fast Fourier transforms (FFT). In general, the signal processing units specially designed to perform the FFT are still expensive and there are lots of calculations because the correlation techniques need much multiplication. Thus, the choice of suitable correlation methods compromising accuracy and economy requirements is of particular importance. Many correlation techniques, which reduce the amount of calculation and are practically implementable, have been investigated by many researchers. Among these, average magnitude difference function (AMDF) and average square difference function (ASDF) have attracted public attention because of their speed. The AMDF and the ASDF are represented as follows:

$$\tilde{\Delta}_{\text{AMDF}} = \arg \min_m \tilde{R}_{\text{AMDF}}(m), \quad \tilde{\Delta}_{\text{ASDF}} = \arg \min_m \tilde{R}_{\text{ASDF}}(m).$$

$$\tilde{R}_{\text{AMDF}}(m) = \frac{1}{N} \sum_{n=0}^{N-m-1} [x[n] - y[n+m]],$$

$$\tilde{R}_{\text{ASDF}}(m) = \frac{1}{N} \sum_{n=0}^{N-m-1} (x[n] - y[n+m])^2,$$

where $\tilde{R}_{\text{AMDF}}(m)$ and $\tilde{R}_{\text{ASDF}}(m)$ represent estimated correlation functions of AMDF and ASDF in a discrete domain, respectively. $\tilde{\Delta}$ is an approximated $\Delta$ from estimated correlation functions and “$\arg \min$” means assumed minimum of $\tilde{R}$ function.

The AMDF does not require any multiplication. Comparing ASDF to AMDF, the ASDF requires more calculations than the AMDF, but it is still effective and reasonably faster than the other correlation methods. As we discussed in Sec. III, the peak level of the obtained sequence varies with the displacement, i.e., $\alpha_{\text{att}}$ is dependent on the displacement. In order to investigate the effect of the $\alpha_{\text{att}}$, simulations were conducted. Figure 8 shows the results of the AMDF and ASDF for the case that $\Delta$ coincides with $\pm 500$ pixels and $\alpha_{\text{att}} = 1, 0.8, 0.6, 0.4, \text{and } 0.2$. 

FIG. 8. The AMDF and ASDF for $\Delta = \pm 500$ pixels and various $\alpha_{\text{att}}$. 

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The results show that the AMDF has a sharp thorn shape around its minimum, \( m = 500 \), while the ASDF has a concave parabola shape. Both the AMDF and ASDF have zero value for \( m = 500 \). However, as \( \alpha \) decreases, the shapes of both correlation estimates are blunted. The diminution of the sensitivity around their minimum makes it difficult to find the minimum position, especially for the AMDF. Thus, in order to realize a real-time signal processing algorithm adequate for the proposed optical triangulation sensor, the ASDF must be considered.

The movement of the peak position of the LID, \( \Delta \), has positive or negative values. However, the existing ASDF cannot deal with negative \( \Delta \) because the correlation variable \( m \) is always zero or a positive integer in the definition of the ASDF. So, we propose improved correlation algorithm expanded ASDF (EASDF) which can process negative \( \Delta \). The EASDF is represented as

\[
\tilde{R}_{\text{EASDF}}(m) = \frac{1}{N} \sum_{n=0}^{N-|m|-1} \left( x \left( n - \frac{m - |m|}{2} \right) - y \left( n + \frac{m + |m|}{2} \right) \right)^2 .
\]

(7)

Although \( \alpha = 1 \), the minimum value of the EASDF must not be zero when \( \Delta \) has a noninteger value because the step size of the correlation variable \( m \) is an integer. The simulation results reveal that a convex parabola can approximate the EASDF in the neighborhood of minimum. Using the approximation, subpixel resolution displacement estimation can be performed by finding the apex of the parabola using three lags of the EASDF.

If

\[
\tilde{R}_{\text{EASDF}}(\tilde{m}_{\text{min}}) \neq 0,
\]

then

\[
\Delta = -\frac{(\tilde{m}_{m-1} + \tilde{m}_{m+1})}{2(\tilde{m}_m - \tilde{m}_{m-1} - \tilde{m}_{m+1})} \left( \mu_3 (\tilde{m}_m - \tilde{m}_{m-1}) - \mu_4 (\tilde{m}_{m-1} - \tilde{m}_{m+1}) \right) ,
\]

where

\[
\mu_3 = \frac{\tilde{R}_{\text{EASDF}}(\tilde{m}_{m-1}) - \tilde{R}_{\text{EASDF}}(\tilde{m}_m)}{\tilde{m}_{m-1} - \tilde{m}_m} ,
\]

\[
\mu_4 = \frac{\tilde{R}_{\text{EASDF}}(\tilde{m}_m) - \tilde{R}_{\text{EASDF}}(\tilde{m}_{m+1})}{\tilde{m}_m - \tilde{m}_{m+1}} .
\]

Figure 9 shows the experimental relationship between converted displacement using the proposed EASDF algorithm and real displacement. The results reveal that the experimental system has an 8 mm linear operation range and a 1 \( \mu m \) resolution without any additional signal processing scheme such as data averaging. The maximum measurement error is approximately 2.4 \( \mu m \) for \( \pm 10^\circ \) inclinations. The commercial system, KEYENCE LC-2440 diffuse reflective type displacement meter has a 6 mm linear operation range, 2 \( \mu m \) reliable resolution with 512 data averaging, and a 10 \( \mu m \) measurement error for \( \pm 10^\circ \) inclination.

V. DISCUSSION

In this article, we proposed the error-reduced optical triangulation sensor system. In order to build up the error-reduced triangulation sensor system, we integrated the incoherent source (LED) and the diffuse reflecting surface with the array detector. Simulation and experimental results showed that only the peak position of the LID was exactly proportional to the object displacement. The peak position of the LID was not affected by the various error sources of the optical triangulation sensors, such as the inclination change of the object surface, light source power fluctuation, and level of ambient light. The results also revealed that the shape of the LID was asymmetric, and the peak level of the LID varied with object displacement. So, a signal processing algorithm converting the peak position of the LID into displacement with the array detector was essential to implement the error-reduced optical triangulation sensor system. To overcome the resolution limited problem of the array detector, we designed the correlation algorithm EASDF that can detect the peak position of the LID with subpixel resolution, referring to the characteristics of the LID. Since the EASDF needed a small amount of multiplication, it was fast enough for real-time implementation without the FFT processor. The experimental optical triangulation sensor system with the EASDF showed an 8 mm linear operation range and 1 \( \mu m \) resolution without averaging and the maximum measurement error was 2.4 \( \mu m \) for \( \pm 10^\circ \) inclinations.

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