Abstract—This paper proposes the phase-stamp range finder (PSRF) for real-time three-dimensional (3-D) imaging. The PSRF consists of a time-domain correlation image sensor (CIS) proposed by us, a scanning sheet of light (SOL), and three-phase reference signals supplied to the CIS. After the SOL was scanned over the object during a frame period, the CIS records the “phase stamp” of the reference signals at the moment when the SOL reflected on the object arrived at each pixel. The range image is then reconstructed at the frame rate by converting the phase stamp image from the CIS pixel-wise to the projection angle of the SOL and then applying triangulation. An experimental system is constructed with a 200 × 200-pixel CIS camera and a light-sectioning laser projection system. Experimental results confirm that the constructed system outputs range images at 12.5 frames/s, achieves measurement accuracy of less than 1 mm in standard deviation for imaging distance of 300–500 mm, and is robust to time-varying, spatially nonuniform ambient illumination and fine surface texture of objects.

Index Terms—Correlation image sensor, light sectioning, phase-stamp imaging, real-time range finder.

I. INTRODUCTION

RANGE finding or three-dimensional (3-D) imaging [1] is a key technology in many advanced applications such as assembly and inspection of industrial products, autonomous robots interacting with human beings and real objects, intelligent transport systems (ITSSs), and virtual/augmented/mixed reality. These applications demand both speed and accuracy for acquiring 3-D range images. From an accuracy standpoint, active range finding methods using an image sensor with light projection are more reliable in real environments than passive methods based on binocular or multiple-camera stereo. Conventional active range finders, however, have difficulty in real-time operation because they require to capture multiple images with video cameras before reconstructing range images.

Active range finders that can operate at video or higher frame rates have recently been proposed. They can be categorized into those based on high-speed cameras [2], [3], high-speed position detection sensors [4]–[6], time-of-flight (TOF) sensors [7]–[11], and time-stamp sensors [12]–[14].

High-speed camera-based range finders are built on conventional range finding techniques such as light-spot projection [2] or structured-light projection [3]. Although the use of high-speed cameras can increase the output rate of range images up to 1000 frames/s or higher, they tend to suffer poor signal-to-noise ratio (SNR) in the images by the decrease in incident light energy as the frame rate becomes higher. Measurement accuracy on the constructed systems was not reported in the literature [2], [3].

Range finders based on position detection sensors [4]–[6] aim to speed up the light-sectioning method by increasing the rate of detecting the position of light sections with specialized CMOS sensors. Fabricated sensors have achieved measurement accuracy in submillimeters for a distance of about 1 m [6]. The peak position of light sections, however, tends to become erroneous under time-varying, spatially nonuniform ambient illumination and for objects with fine surface texture because of intensity-based detection of peak positions.

TOF sensors can be divided into CCD-based sensors [7], [8], CMOS sensors [9], and Axi-Vision Cameras [10], [11]. They measure the distance pixel-wise by measuring the traveling time of projected modulated light that is reflected on objects without interpixel image processing. In the VLSI TOF sensors, the nature of silicon devices has limited the range resolution to centimeters, although a remarkable progress has recently been made in a CMOS sensor that realized millimeter resolution [9]. The Axi-Vision Cameras, which perform TOF measurement using an image intensifier as a high-speed electronic shutter, are not easy to access for practical use. The range resolution of the Axi-Vision Cameras has also been limited to millimeters [11].

Time-stamp range finders (TSRFs) [12]–[14] were realized with specialized VLSI array sensors working on a different sensing principle from conventional light sectioning, though they use the same imaging geometry. In a TSRF, for a sheet of light (SOL) scanned over the object, the VLSI sensor outputs an image of the “time stamp” when the light arrived at each pixel of the sensor by recording the value of an external reference signal at this moment. After a scan of the SOL, the TSRF recovers the distance to objects pixel-wise by converting the time stamp to the projection angle of the SOL and then applying triangulation. One of the TSRFs reported measurement accuracy of less than 0.1 mm for a distance of about 300 mm [14]. While the proposed TSRFs do not need interpixel image processing as with the TOF sensors, their intensity-based detection of time stamps
makes them vulnerable to time-varying, spatially nonuniform ambient illumination and fine surface texture of objects, as with the position detection sensor-based range finders.

To develop a real-time range finder that is robust to ambient illumination and surface texture, we first applied the time-domain correlation image sensor (CIS) to a light-sectioning range finder [15]. The CIS, proposed and developed by us [16], produces the temporal correlations at each pixel between the intensity signal of incident light and external reference signals over a frame period, and outputs the correlations as images. In this range finder, the intensity of the SOL is sinusoidally modulated while its phase is gradually shifted by $2\pi$ over a scan of the SOL. During this scan, the CIS captures correlation images of objects illuminated with the SOL while supplied with reference signals of the same frequency as the SOL modulation. This arrangement allows the CIS to demodulate the SOL phase at the arrival time of the SOL at each pixel. Although this range finder appears similar to TSRFs, the temporal correlation principle gives an advantage in robustness to time-varying, spatially nonuniform ambient illumination and fine surface texture of objects. As a drawback, this range finder requires a higher frequency for SOL modulation and reference signals than the frame rate of the CIS in order to demodulate the SOL phase within a very short time with good accuracy. This could decrease sensor gain and shift the demodulated phase according to low-pass frequency response of the CIS [17]. We have later developed this range finder into a more advanced one by use of a kind of structured light called spatio-temporal phase-encoding illumination [18].

In this paper, we propose a novel real-time range finder using the CIS, called phase-stamp range finder (PSRF) [19], [20]. The PSRF, as in our previous range finder, can output range images at the frame rate of the CIS, and also is robust to ambient illumination and surface texture. The PSRF employs the same imaging geometry as our previous one, but is made simpler without SOL modulation. In the PSRF, the CIS records the “phase stamp” of the reference signals at the arrival time of the SOL instead of the modulation phase of the SOL. As another advantage, the reference signal frequency can be as low as the frame rate of the CIS. In the previous reports [19], [20], the PSRF was not optimized because of undesirable artifacts in the output range images. This paper presents new results on accuracy and robustness to ambient illumination and surface texture by incorporating an error compensation method for removing the artifacts [21].

The rest of this paper is organized as follows. Section II describes the sensing principle of the proposed PSRF. Section III describes the experimental system. Section IV shows experimental results on the accuracy of the developed PSRF system and on the robustness to ambient illumination and surface texture. Finally, Section V concludes this paper.

II. PHASE-STAMP RANGE FINDER

A. Time-Domain Correlation Image Sensor

The most important component of the PSRF is the CIS, which is illustrated in Fig. 1. The CIS has three signal inputs $g_k(t)$ ($k = 1, 2, 3$) called reference signals, constrained with $g_2(t) + g_3(t) = 0$. Let us denote the intensity of incident light at pixel $(i, j)$ by $f_{ij}(t)$. Then, after a frame period $T$ of the CIS, each pixel $(i, j)$ produces three outputs $Q_k(i, j)$ ($k = 1, 2, 3$) expressed as [16]

$$
\begin{bmatrix}
Q_1(i, j) \\
Q_2(i, j) \\
Q_3(i, j)
\end{bmatrix} = \begin{bmatrix}
\Delta Q_1(i, j) \\
\Delta Q_2(i, j) \\
\Delta Q_3(i, j)
\end{bmatrix} + \begin{bmatrix}
\langle f_{ij}(t) \rangle / 3 \\
\langle f_{ij}(t) \rangle / 3 \\
\langle f_{ij}(t) \rangle / 3
\end{bmatrix}
$$

$(1)$

$$
\Delta Q_k(i, j) = \langle f_{ij}(t) g_k(t) \rangle \quad (k = 1, 2, 3)
$$

$(2)$

where $\langle \cdot \rangle$ denotes a time integral over $T$. The first term of the right-hand side of (1), $\Delta Q_k(i, j)$, represents the temporal correlation between $f_{ij}(t)$ and $g_k(t)$, whereas $\langle f_{ij}(t) \rangle$ in the second term is proportional to the average light intensity. From $Q_k(i, j)$, $f_{ij}(t)$ and $\Delta Q_k(i, j)$ are obtained as

$$
\langle f_{ij}(t) \rangle = Q_1(i, j) + Q_2(i, j) + Q_3(i, j)
$$

$(3)$

$$
\Delta Q_k(i, j) = Q_k(i, j) - \frac{1}{3} \langle f_{ij}(t) \rangle
$$

$(4)$

\Delta Q_k(i, j) ($k = 1, 2, 3$) have two degrees of freedom in total because the constraint $\sum_{k=1}^{3} g_k(t) = 0$ gives $\sum_{k=1}^{3} \Delta Q_k(i, j) = 0$.

B. Single-Frame 3-D Measurement by Phase-Stamp Imaging

Now, we describe the PSRF, following the original formulation [19], [20]. The PSRF consists of a CIS camera, a sheet of light, a scanning mirror, and a reference signal generator, as depicted in Fig. 2. The imaging geometry of the PSRF is similar to that of the light-sectioning range finder. When the light projected at an angle $\theta$ is reflected on a surface point of the object and imaged onto a pixel $(i, j)$ of the CIS, the depth $z_{ij}$ of the surface point from the CIS is computed by triangulation as

$$
z_{ij} = \frac{L_x \tan \theta + L_z}{1 - \frac{F}{F} \tan \theta}
$$

$(5)$

where $F$ and $\Delta x$, respectively, denote the distance of the image plane from the lens center of the CIS camera and the pixel.
spacing along the $x$ axis, and $L_x$ and $L_z$ are the distances defined in Fig. 2. Equation (5) implies that the range image $z_{ij}$ is obtained if the projection angle $\theta$ is known at each pixel.

The main idea of the PSRF is to detect $\theta$ at each pixel $(i,j)$ without any interpixel computation after image capture. To obtain a map of $\theta$, we scan the SOL over the object once during a frame period of the CIS. We note that the projection angle $\theta(t)$, expressed as a function of time $t$, can be known beforehand as a design parameter. The light intensity $f_{ij}(t)$ observed at a pixel $(i,j)$ is then expressed with a Dirac delta function $\delta(t)$ as

$$f_{ij}(t) = R_{ij} \left[ A_{ij} \delta(t - t_{ij}) + B_{ij}(t) \right]$$  \hspace{1cm} (6)

where $R_{ij}$, $A_{ij}$, $B_{ij}(t)$, and $t_{ij}$, respectively, denote the surface reflectance of the object, the total SOL energy, the intensity of ambient illumination, and the time stamp at which the SOL is detected at $(i,j)$. Meanwhile, we supply to the CIS three-phase sinusoidal reference signals $g_k(t)$ of the same frequency $f_0 = T^{-1}$ as the frame rate of the CIS with phase difference of $(2/3)\pi$ from each other, as

$$g_k(t) = \cos \left[ 2\pi f_0 t + \frac{2}{3} \pi (k - 1) \right] \quad (k = 1, 2, 3).$$  \hspace{1cm} (7)

It is reasonable to assume $B_{ij}(t)$ to be uncorrelated with the sinusoidal reference signals $g_k(t)$, so that

$$\langle B_{ij}(t) g_k(t) \rangle \approx 0.$$  \hspace{1cm} (8)

Substituting (6), (7) and (8) into (2) then gives temporal correlation images $\Delta Q_k(i,j)$ after a frame period as

$$\begin{bmatrix} \Delta Q_1(i,j) \\ \Delta Q_2(i,j) \\ \Delta Q_3(i,j) \end{bmatrix} = R_{ij} A_{ij} \begin{bmatrix} \cos \psi_{ij} \\ \cos \left( \psi_{ij} + \frac{2}{3} \pi \right) \\ \cos \left( \psi_{ij} + \frac{4}{3} \pi \right) \end{bmatrix} + \begin{bmatrix} \xi_1(i,j) \\ \xi_2(i,j) \\ \xi_3(i,j) \end{bmatrix}$$  \hspace{1cm} (9)

where $\psi_{ij} = 2\pi f_0 t_{ij}$ is the phase of reference signal $g_k(t)$ at time $t_{ij}$ and $\xi_k(i,j)$ ($k = 1, 2, 3$) account for noise contributions. The term $\psi_{ij}$ is called “phase stamp” at the arrival time of the SOL onto pixel $(i,j)$. $\psi_{ij}$ is the key to determining the projection angle $\theta_{ij}$ for each pixel $(i,j)$ as

$$\theta_{ij} = \theta(t_{ij}) = \theta \left( \frac{\psi_{ij}}{2\pi f_0} \right).$$  \hspace{1cm} (10)

The timing relation among projection angle $\theta(t)$, incident light intensity $f_{ij}(t)$, three-phase reference signals $g_k(t)$ ($k = 1, 2, 3$), and the phase of $g_1(t)$, $\psi(t) = 2\pi f_0 t$, is illustrated in Fig. 3. The phase stamp image $\psi_{ij}$ is obtained from (9) by least-squares estimation as [16]

$$\psi_{ij} = \tan^{-1} \frac{\sqrt{3} (\Delta Q_2 - \Delta Q_3)}{2 \Delta Q_1 - \Delta Q_2 - \Delta Q_3}$$  \hspace{1cm} (11)

where $(i,j)$ is omitted from $\Delta Q_k$ for simplicity. The range image $z_{ij}$ is thus obtained from the single-frame temporal correlation images $\Delta Q_k(i,j)$ by (11), (10) and (5) at the frame rate of the CIS. The intensity image $I_{ij} = R_{ij} A_{ij}$ produced by the SOL alone is also derived as

$$I_{ij} = \frac{\sqrt{2}}{3} \left[ (\Delta Q_1 - \Delta Q_2)^2 + (\Delta Q_2 - \Delta Q_3)^2 + (\Delta Q_3 - \Delta Q_1)^2 \right]^{\frac{1}{2}}.$$  \hspace{1cm} (12)

In the principle above, the PSRF removes $B_{ij}(t)$ through temporal correlation in (8), and cancels both $R_{ij}$ and $A_{ij}$ in the computation of $\psi_{ij}$ in (11). This makes the PSRF robust to time-varying, spatially nonuniform ambient illumination and fine surface texture of objects.

### III. EXPERIMENTAL SYSTEM

Fig. 4 shows a photograph of the experimental system, comprised of a 200 × 200-pixel CIS camera [18], a scanning mirror module (General Scanning Inc. XY30M3S), and
The laser beam was expanded into a sheet through optics and scanned back and forth horizontally by the mirror at 25 scans/s. Three-phase reference signals with a frequency of 50 Hz were generated from a digital-to-analog board on another PC. Their waveforms were reversed in time in every other period, as depicted in Fig. 6. This reversion ensures that each pixel of the CIS always accumulates the same temporal correlation values \( \Delta Q_k(i, j) = R_{ij} A_{ij} \cos[\psi_{ij} + (2/3)(k - 1)\pi] \) \((k = 1, 2, 3)\) of phase stamp \( \psi_{ij} \) for the same projection angle \( \theta \) of the SOL, four times in a single frame regardless of the forward or backward scanning direction of the SOL. The true phase stamp \( \psi_{ij} \) corresponding to the actual projection angle \( \theta \) can thus be recovered from the accumulated \( \Delta Q_k(i, j) \).

The geometry of the CIS camera and the SOL were calibrated with respect to a world coordinate frame. The internal and external parameters of the CIS camera were estimated with a camera calibration method \[22\]. From the characteristic of the scanning mirror module, the projection angle \( \theta(t) \) of the SOL was assumed to be linear to time \( t \), and thus to the actual phase of the three-phase reference signals.

We have found that detected phase stamps \( \psi_{ij} \) exhibit two kinds of errors—nonlinearity to actual time stamps \( t_{ij} \) of SOL incidence and fixed-pattern noise that periodically varies with \( t_{ij} \), which were absent in CIS applications involving sinusoidally modulated illumination \[18\], \[23\]. For a flat object, these errors give rise to artifacts of a waving pattern and a random noise pattern in the reconstructed range image. In the experiments described next, we applied a method for compensating for these errors \[21\].

**IV. RESULTS**

**A. Accuracy Evaluation**

First, we evaluated the accuracy of the constructed PSRF system. The object was a flat board painted uniformly with white diffuse material. The distance of the object from the CIS camera was changed from 300 to 500 mm in 50 mm steps. All the results were obtained without ambient illumination.

Fig. 7 shows the results for the object placed at about 400 mm in front of the CIS camera. Fig. 7(a)–(c) are the images of average intensity \( I_{ij} \), SOL intensity \( I_{ij} \), and phase stamp \( \psi_{ij} \). The phase stamp, coded as shown in Fig. 7(d), increases monotonically from left to right owing to horizontal scan of the SOL.

TABLE I

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>CMOS 0.35 ( \mu )m 2P3M</td>
</tr>
<tr>
<td>Image size</td>
<td>200 ( \times ) 200</td>
</tr>
<tr>
<td>Pixel size</td>
<td>40 ( \mu )m ( \times ) 40 ( \mu )m</td>
</tr>
<tr>
<td>Chip size</td>
<td>9.8 mm ( \times ) 9.8 mm</td>
</tr>
<tr>
<td>Phase SNR</td>
<td>( \sim 44 ) dB</td>
</tr>
<tr>
<td>Cutoff frequency</td>
<td>( 400 \times ) (frame rate) Hz</td>
</tr>
<tr>
<td>Frame rate</td>
<td>1.875 ( \sim 15 ) frames/s</td>
</tr>
</tbody>
</table>

**Fig. 4.** A photograph of the experimental PSRF system.

**Fig. 5.** A photograph of the 200 \( \times \) 200 CIS camera.

**TABLE I**

**SPECIFICATIONS OF THE 200 \( \times \) 200-PIXEL CIS CAMERA**

*Fig. 6.** Timing relation among projection angle \( \theta(t) \), three-phase reference signals \( g_k(t) \) \((k = 1, 2, 3)\), and phase stamp \( \psi(t) \) in the experimental PSRF system.
Fig. 7. Results of the PSRF for a flat object placed at about 400 mm in front of the CIS camera. (a) Average intensity image \( f_{i,j}(t) \). (b) SOL intensity image \( I_{i,j} \). (c) Phase stamp image \( \psi_{i,j} \). (d) Grayscale chart of phase stamp. (e) Profiles of \( f_{i,j}(t) \) and \( I_{i,j} \) along \( j = 150 \) as marked by the white lines in (a) and (b). (f) 3-D plot of reconstructed range image \( z_{i,j} \). (g) Profile of \( z_{i,j} \) along \( j = 150 \) as marked by the white line in (e).

Table II
Accuracy of the Constructed PSRF System

<table>
<thead>
<tr>
<th>Range setting [mm]</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systematic offset</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase [deg]</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Range [mm]</td>
<td>0.01</td>
<td>0.02</td>
<td>0.06</td>
<td>0.10</td>
<td>0.13</td>
</tr>
<tr>
<td>Standard deviation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase [deg]</td>
<td>1.03</td>
<td>1.02</td>
<td>1.21</td>
<td>1.20</td>
<td>1.18</td>
</tr>
<tr>
<td>Range [mm]</td>
<td>0.36</td>
<td>0.49</td>
<td>0.70</td>
<td>0.78</td>
<td>0.88</td>
</tr>
</tbody>
</table>

except at a jump from \( \pi \) to \(-\pi\). This \( 2\pi \) phase jump was unwrapped before converting the phase to the projection angle of the SOL, by simply searching for an abrupt decrease of phase from left to right along each horizontal line. Fig. 7(f) plots horizontal profiles of the average intensity image \( \langle f_{i,j}(t) \rangle \) and the SOL intensity image \( I_{i,j} \) along \( j = 150 \) as marked by the white lines in Fig. 7(a) and (b). The two profiles coincide well as expected because ambient illumination was absent. The nonuniform pattern in Fig. 7(a) and (b) was mainly caused by spatial intensity distribution of the SOL and surface defects of the scanning mirror. These factors jointly produced an interference pattern by diffraction along the intensity profile of the SOL, thus introducing nonuniformity in the images of \( \langle f_{i,j}(t) \rangle \) and \( I_{i,j} \). This nonuniformity could make some pixels too dark or too bright to allow reliable computation of phase stamps. It can be suppressed, however, by use of more sophisticated SOL optics and a scanning mirror with a cleaner surface. Fig. 7(f) shows a 3-D plot of the range image \( z_{i,j} \) reconstructed from the phase...
Fig. 9. Results of the PSRF for a flat object placed at about 400 mm in front of
the CIS camera, obtained under sinusoidally modulated ambient illumination.
See Fig. 8 for description of (a)–(f).

Fig. 10. Results of the PSRF for a flat object placed at about 400 mm in front
of the CIS camera, obtained with vertical fringe surface texture. See Fig. 8 for
description of (a)–(f).

Table II summarizes the accuracy of the phase stamp image
and the range images for distances from 300 to 500 mm, in terms
of systematic offset of the average from the theoretical value and
standard deviation from the average. The values were calculated
over the entire image region, with pixels with too low or too high
excluded for the reason mentioned above. The standard deviation
was about 1° in phase stamp, and kept less than 1 mm in range with a slight increase from 300 to 500 mm.
The systematic offset of phase stamp was zero for all the range
settings because the system geometry was so calibrated. This led
to the systematic offset of range suppressed to about 0.1 mm.

B. Effect of Ambient Illumination and Surface Texture

Next, we investigated the effect of ambient illumination and
surface texture on the accuracy of the PSRF. With the object
board placed at about 400 mm, we either projected a static vertical fringe pattern or a sinusoidally modulated uniform illumination as ambient illumination, or attached a sheet of a vertical fringe pattern on the object as surface texture. The pitch of the vertical fringes of the ambient illumination and the surface texture was about four to six pixels. The frequency of the sinusoidal modulation was 200 Hz. The intensity of the ambient illumination was comparable to that of the SOL both in the vertical fringe and sinusoidal modulation cases. The reflectance of dark fringes of the surface texture was about 75% of bright fringes.

Figs. 8–10 show the results for the fringe ambient illumination,
for the modulated ambient illumination, and for the fringe surface texture, respectively. In Figs. 8 and 9, the SOL intensity
was reduced to half of that in Fig. 7 in order to keep the CIS
Fig. 11. Results of the PSRF for a flat object placed at about 400 mm in front of the CIS camera, obtained without ambient illumination nor surface texture. The SOL intensity was reduced to half of that in Fig. 7. See Fig. 8 for description of (a)–(f).

below saturation. This reduction is observed in Figs. 8(d) and 9(d), which show the profiles of the average and SOL intensity images along the white lines in Figs. 8(a), (b) and 9(a), (b), respectively, in comparison to the profiles in Fig. 7(e). We note in Fig. 8 that the vertical fringe pattern of the ambient illumination is observed only in the average intensity image in Fig. 8(a) but not in the SOL intensity and phase stamp images in Fig. 8(b) and (c), thanks to the temporal correlation in (8). The almost same level of the SOL intensity image for the sinusoidally modulated ambient illumination in Fig. 9(b) as that for the vertical fringe ambient illumination in Fig. 8(b) also demonstrates the effectiveness of the temporal correlation in suppressing time-varying ambient illumination. The suppression of ambient illumination is further confirmed in the intensity profiles in Figs. 8(d) and 9(d), where the difference between the average and SOL intensity profiles accounts for the ambient illumination. In Fig. 10, the vertical fringe pattern of the surface texture can be observed both in the average intensity and SOL intensity images in Fig. 10(a) and (b) as well as in the intensity profiles in Fig. 10(d), but is entirely canceled in the phase stamp image in Fig. 10(c) by the phase retrieval in (11). In the 3-D plots and horizontal profiles along of reconstructed range images in Figs. 8(e), (f) and Figs. 10(e), (f), no periodic vertical stripe patterns associated with the ambient illumination or the surface texture can be recognized. In summary, the results in Figs. 8–10 confirm the robustness of the proposed PSRF to time-varying, spatially nonuniform ambient illumination and fine surface texture.

It is noticeable that the 3-D plots and horizontal profiles for nonzero ambient illumination in Figs. 8 and 9(c) and (f) look noisier than those in Fig. 7(f) and (g). By contrast, the plots for surface texture in Fig. 10(e) and (f) have a similar fluctuation level to those in Fig. 7(f) and (g). To investigate this phenomenon, we imaged the object board with the same SOL intensity as in Figs. 8 and 9 but without ambient illumination nor surface texture. Fig. 11 shows the results of reducing the SOL intensity

<table>
<thead>
<tr>
<th>Table III</th>
<th>EFFECT OF AMBIENT ILLUMINATION AND SURFACE TEXTURE ON THE ACCURACY OF THE CONSTRUCTED PSRF SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background illumination</td>
<td>—</td>
</tr>
<tr>
<td>Surface texture</td>
<td>—</td>
</tr>
<tr>
<td>SOL intensity</td>
<td>×1</td>
</tr>
<tr>
<td>Systematic offset</td>
<td>Phase [deg]</td>
</tr>
<tr>
<td>Range [mm]</td>
<td>0.06</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>Phase [deg]</td>
</tr>
<tr>
<td>Range [mm]</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Fig. 12. Results of the PSRF for a can. (a) SOL intensity image \( I_{ij} \). (b) Phase stamp image \( \psi_{ij} \). (c) 3-D plot of reconstructed range image \( z_{ij} \).
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Fig. 13. Results of the PSRF for a box. See Fig. 12 for description of (a)–(c).

Fig. 14. Results of the PSRF for a roll of paper. See Fig. 12 for description of (a)–(c).

as shown in the intensity profiles in Fig. 11(d). The 3-D plot and horizontal profile in Fig. 11(e) and (f) exhibit a similar level of noisiness to those in Figs. 8 and 9(e) and (f). Table III lists systematic offset and standard deviation of the phase stamp images and range images for the results in Figs. 7–11. It is recognized that the standard deviation for lower SOL intensity is larger than that for higher SOL intensity. We suspect that this increase in standard deviation was due to lower SNR in the phase-stamp imaging because of the lower SOL intensity.

Fig. 15. Results of the PSRF for a sculpture. See Fig. 12 for description of (a)–(c).

C. Examples of Range Imaging

Figs. 12–15 show the results of imaging a can, a box, a roll of paper, and a sculpture with the constructed PSRF. All the objects were placed about 400 mm in front of the CIS camera. The 3-D surfaces are reconstructed in good accordance with the actual shape of the objects.

V. CONCLUSION

A real-time 3-D imaging system called phase-stamp range finder has been proposed. The PSRF, consisting of a CIS camera, a scanning SOL, and three-phase reference signals, can output range images at a video frame rate based on the phase-stamp imaging technique. The experimental results have demonstrated real-time range imaging at 12.5 frames/s, measurement accuracy of less than 1 mm in standard deviation for imaging distance of 300–500 mm, and robustness to time-varying, spatially nonuniform ambient illumination and fine surface texture of objects. The results confirm that the PSRF is useful to real-time 3-D imaging of objects with surface texture under ambient illumination.

REFERENCES


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