Optica Applicata, Vol. XLVII, No. 4, 2017
DOI: 10.5277/oa170404

Range resolution improvement of range-gated vision system in backscattering hazy environments

Seung-Kyu Park[1*], In-Young Choi[1], Sung-Hoon Baik[1], Kyung-Min Jeong[2]

[1]Quantum Optics Research Division, Korea Atomic Energy Research Institute, Daejeon 305-353, Republic of Korea

[2]Nuclear Robotics Lab, Korea Atomic Energy Research Institute, Daejeon 305-353, Republic of Korea

[*]Corresponding author: skpark4@kaeri.re.kr

A range-gated vision system simultaneously provides two-dimensional and range images because its light intensity contains the reflectance as well as depth information. The range-resolution of the system is usually inversely proportional to the induced backscattering noise. In this paper, a range imaging technique is proposed to precisely measure range information from highly backscattering foggy environments. A windowed center-of-mass position extracted from the peak area of a cross -correlation signal of two signals, a Gaussian window signal in reduced size and a range-gated signal according to distance, is adopted as the range depth. The proposed measuring technique provides more robust and more precise range information than conventional measuring techniques for hazy targets by virtue of the reduction of backscattering bias noise usually induced by airborne particles. The experimental results and the signal processing procedures to acquire precise range information from hazy targets are described in this paper.

Keywords: range-gated vision system, range image, windowed center-of-mass, cross-correlation, Gaussian window.

1. Introduction

Range-gated imaging is an active vision system that is basically composed of a synchronized high-speed gating camera with a pulse laser. The vision system can simultaneously provide 2D and range information. Though the system is capable of minimizing backscattering noise effects from airborne particle media owing to its short-range gating characteristic, the measuring resolution is still decreased in proportion to the density of airborne backscattering particles.

Various ranging technologies have been studied for target recognition in clear and hazy environments, such as through airborne fog particles [1–3] and in turbid underwater media [4, 5]. The range imaging capability of a system depends highly on the presence and concentration of backscattering particles in the media [6, 7]. In principle, range information is acquired by finding the arrival time of the maximum intensity value from sequentially gated images along the range direction [8–16]. For example, range is acquired from the image pixel with peak intensity in a range-gated image sequence [8]. The high-speed measuring technique is simple but it is sensitive to noise such as the intensity variation of illumination laser light. Also, the range resolution is too low as it is not better than the corresponding length of a delay step. Range information can be quickly acquired by using the intensity ratio among overlapping neighbor range-gated images. This technique is suitable for acquiring long-range information and its range resolution is vulnerable to noise [9, 10]. As a technique to improve the resolution, precise range information is acquired from the peak detection of a fitting curve of a range -gated intensity profile along the range direction [3, 11, 12]. Although this provides improved range resolution, it is sensitive to noises and requires time consuming computations. Precise range information can also be acquired from the center-of-mass (COM) position of a thresholded range-gated signal along the range direction [13–16]. Although this fast measuring technique is widely used by virtue of its simplicity and robustness to induced random noise, it is still vulnerable to the biased backscattering noise. In addition, the COM position, by considering the distance effect on the reflected illumination light, improves the range accuracy in a clean environment [17]. However, it also remains vulnerable to foggy environments because it does not consider the effects of varying reflection caused by spatially varying fog density.

In general, the variation in intensity of the illumination laser light is extremely high because of its inherent interference characteristics and the intensity instability of short -pulsed laser light, such as the speckle noise and the high variation of the lasing dispersion angle. Although the intensity variation can be reduced through an averaging of multiple illuminations, non-negligible variation noise remains and, in some cases the averaging technique cannot be used if the repetition rate of the pulse laser is slow. The measuring technique using the COM position is robust to speckle pattern noise and the intensity variation noise of the illumination laser light. Thus, a range-gated vision system using this technique can provide precise range information in a clean environment. But its range resolution measured from hazy environments, such as through airborne fog or smoke particles, is rapidly decreased because the measurement error is increased by the backscattering bias noise induced by the airborne particles.

In this paper, a short-range imaging technique useful in hazy environments of scattering bias noise is proposed. A windowed COM position extracted from the peak area of a cross-correlation signal of two signals, a Gaussian window signal in reduced size and a range-gated signal according to distance, is adopted as the range information for each pixel position of an image. The technique provides more robust and more precise range information than does the conventional measuring technique using the COM position for monitoring hazy targets. The signal processing technique with experimental results to acquire range images in foggy environments is described in this paper.

2. Configuration of a range-gated vision system in a backscattering noise environment

A range-gated vision system is configured to monitor short-range hazy targets in a test room. A block diagram and a photograph of the system are respectively shown in Figs. 1 and 2.

The system consists of an illumination pulse laser (power chip laser, wavelength 532 nm, Teem Photonics, Inc.), an intensified fast-gating camera (ICCD: 4-Picos-Dig,

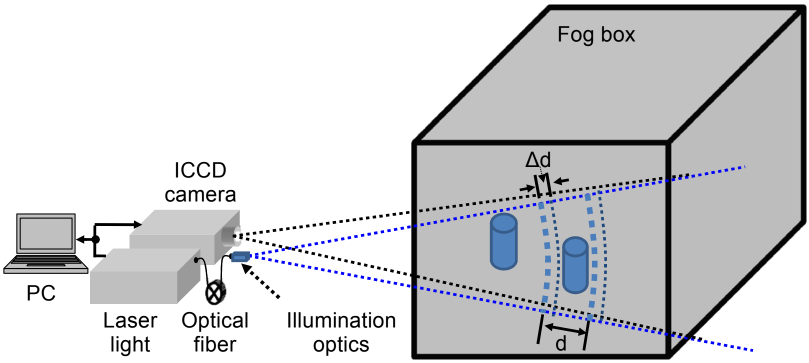

Fig. 1. Block diagram of the configured range-gated vision system.

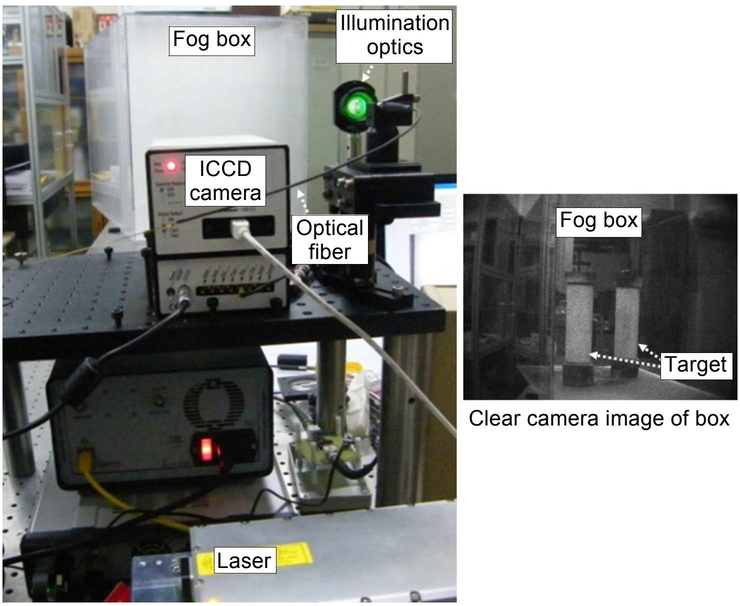

Fig. 2. Photograph of the configured range-gated vision system.

Stanford Computer Optics, Inc.), an optical fiber of 60 m, illumination optics, and a control computer (PC, CPU-I7). The vision system adopts a short pulse laser illuminator for use in backscattering hazy environments. The illuminator is a diode-pumped passively Q-switched microchip solid-state laser at 532 nm with a pulse width of about 400 ps, and its average energy per pulse is about 40 μJ. The laser light illuminates targets through an optical fiber and illumination optics. An optical fiber is used to delay the illumination time for synchronizing between the illuminator and camera. The intensity and divergence angle of the illumination light are controlled through the illumination optics.

As shown in Figs. 1 and 2, a range-gated image within a time-sliced space d is captured by an intensified CCD (ICCD) camera. The camera shifts the measuring space by delaying the capturing time (Δd), as shown in Fig. 1. The camera contains a CCD chip with 680 × 512 pixels and a highly sensitive multi-channel-plate (MCP) with a quantum efficiency of around 16% at 532 nm. A range-gated image is captured by the ICCD camera triggered by each individual laser pulse. Sequentially, range-gated images along the range direction are acquired by delaying the acquisition time of the camera.

3. Comparison of range measurement methods, experiments, and discussion

In foggy environments, mainly two types of non-negligible noises exist in a range-gated active vision system. One is the intensity drift of illumination light caused by the instability of lasing pulse and the other is the backscattering bias noise caused by airborne fog particles. The former can be reduced by averaging because it usually has a random pattern but the latter is not reduced by averaging. These noises may decrease the measurement resolution of the vision system. As previously described, the range measurement based on the COM position is robust to random noise usually induced by the instability of the pulse laser but it is still vulnerable to the backscattering bias noise, which is usually exponentially decreased nearby the target surface [18, 19].

As is well known, a range image $r(x, y)$ of the conventional technique using the COM position is acquired according to the following equation:

$$r(x,y) = \frac{c}{2n}\left\{d_0 + \Delta d\left[\frac{\sum_{i=1}^{N_s}\left|I_i(x,y)-\theta(x,y)\right| i}{\sum_{i=1}^{N_s}\left|I_i(x,y)-\theta(x,y)\right|}\right]\right\}$$

where Δd is the acquiring delay step of the camera, d_0 is the basic camera delay, c is the speed of light, n is the refractive index, $I_i(x, y)$ is the pixel intensity of the i-th acquired range-gated image, and $\theta(x, y)$ is the threshold at the image position (x, y).

Simulation graphs of range-gated signals according to distance in foggy environments are shown in Fig. 3. Here, “A” is an ideal range-gated profile of the Gaussian pattern according to distance, “B” is its mixed signal with noise, and “C” is added

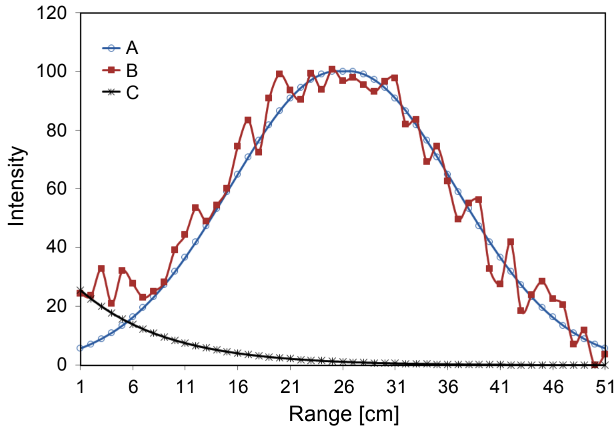

Fig. 3. Simulation graphs of range-gated signals in backscattering noise environments.

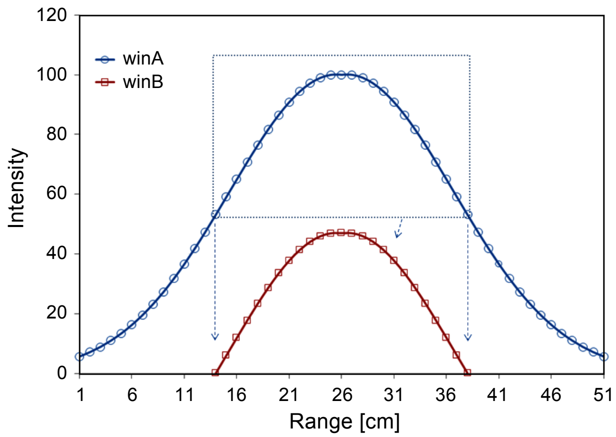

Fig. 4. Gaussian window signal for cross-correlation.

backscattering bias noise usually generated by airborne scattering particles [18, 19]. The intensity is a grayscale value from 0 to 255 for each pixel in a range-gated image.

To reduce both types of noise effects, a window signal of a Gaussian pattern with reduced size is adopted, as shown in "winB" of Fig. 4. The Gaussian window signal "winB" is the upper half of "winA", which is a conventional pattern of an ideal range -gated signal profile, as shown in "A" of Fig. 3. We selected the Gaussian window signal to extract the range signal component from a range-gated signal profile because the range-gated signal determined by the convolution of the pulse laser signal and the gating sensor signal usually has this Gaussian pattern, and the target range position is the highest intensity position in the entire signal [8]. The half size of the range-gated signal was selected for the correlation window signal to reduce the biased backscattering noise effect. The range signal component of "winB" is extracted from a noisy range-gated signal profile of "B" in Fig. 3 by acquiring a cross-correlation signal of

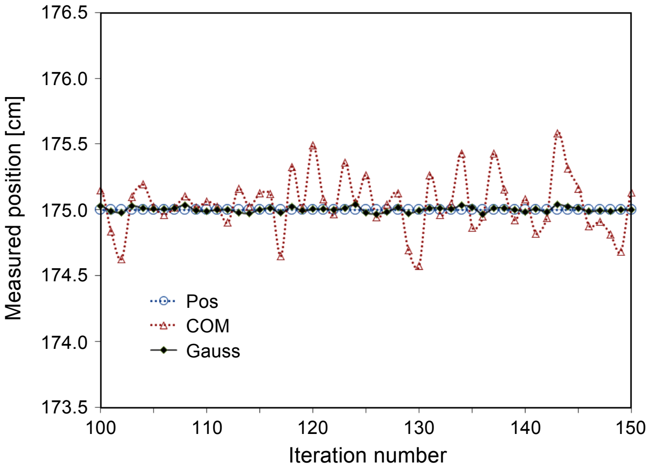

Fig. 5. Comparison of measured range positions in a random noise environment.

two signals (*i.e.*, "winA" and "B"), and then precise range information is calculated from the peak area of the cross-correlation signal using the windowed COM position. The range resolution calculated from the cross-correlation signal is improved through the amplification of the range signal component.

Some of the measured positions from a target surface in a random generated noise environment are shown in Fig. 5. Here, the signal of "Pos" displays the surface positions of the target and "COM" displays the positions measured by the conventional technique using the COM position. The notation "Gauss" displays the results measured by the windowed COM position from the cross-correlation signal of a range-gated signal and the Gaussian window signal "winB" of Fig. 4. Here, the window size to extract the COM position from the peak area of the cross-correlation signal was 1 × 11. For each iteration, newly generated random noise was added and then the grayscale signal intensity mixed with noise was thresholded by 10. The grayscale intensity of the generated random noise was within the range –10 to 10. As shown by the "Gauss" signal of Fig. 5, the proposed measuring technique provides the position of the target with greater precision compared to the conventional technique "COM". The average values of absolute measurement errors of "COM" and "Gauss" for 300 experiments were 0.18 and 0.06 cm, respectively.

Some of the measuring results from the additionally added backscattering bias noise, such as the "B" signal of Fig. 3, are shown in Fig. 6. The grayscale of the maximum intensity of the backscattering bias noise, such as the "C" signal of Fig. 3, was within the range 20–40 and the grayscale intensity range of the random noise was –10 to 10. The signal notations, "Pos", "COM", and "Gauss", are the same as in Fig. 5. The signal of "COM(LPF)" is the measuring result of "COM" after using a zero-phase low-pass -filter (LPF) of a 1 × 11 pixel window. As shown in Fig. 6, the "Gauss" method provides more precise range information than the conventional methods. As shown here,

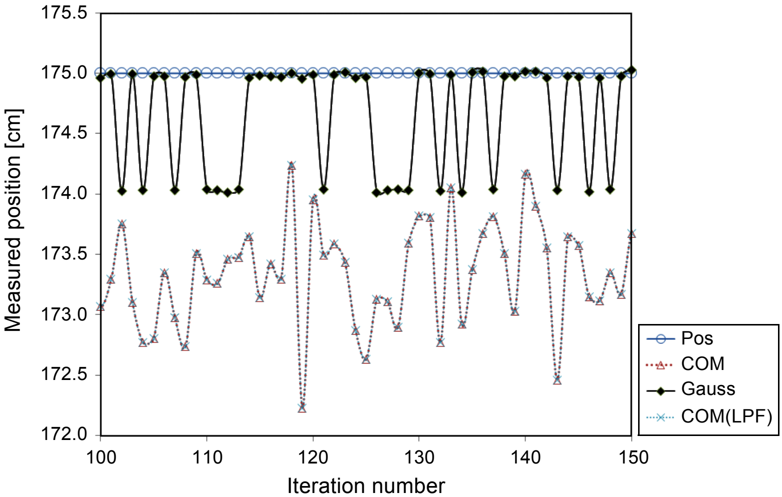

Fig. 6. Comparison of measured range positions in backscattering noise environments.

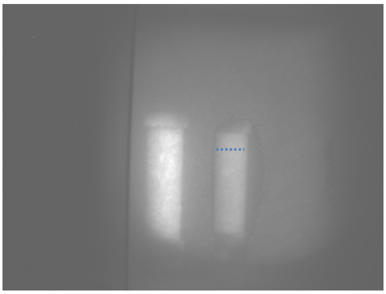

Fig. 7. Normalized two-dimensional image acquired from hazy targets.

"COM" and "COM(LPF)" provide similar measuring results because the LPF was not effective against the backscattering bias noise. The average error values of "COM", "COM(LPF)", and "Gauss" for 300 experiments were 1.70, 1.70, and 0.30 cm, respectively.

A normalized 2D image measured from 75 range-gated images with a delaying step distance of 0.6 cm in a no visibility foggy environment of Fig. 2 is shown in Fig. 7. Here, three images are averaged to acquire each range-gated image. As shown by the results, the vision system provided a distinct 2D-image from a no visibility foggy environment. Here, the targets are two metal tubes (W = 10 cm, H = 42 cm) installed in a transparent fog box. The distances between the illumination laser and the specimens are about 207 and 230 cm.

The range images acquired from "COM", "COM(LPF)", and "Gauss" are shown in Fig. 8. Here, the highest intensity part composed of 47 data (N_S) in a sequence of range gated images is only used for the signal processing and the grayscale intensity values

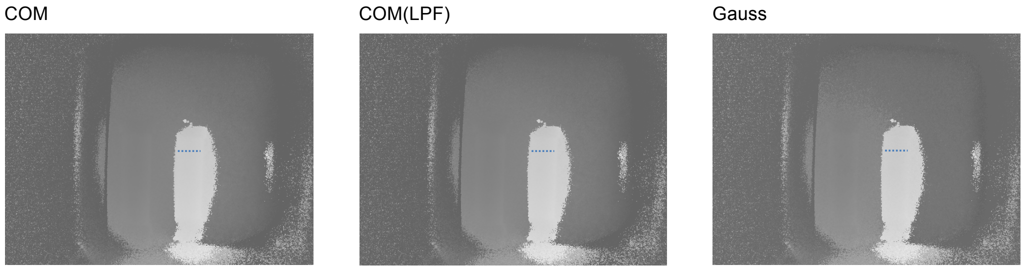

Fig. 8. Comparison of range images acquired from hazy targets.

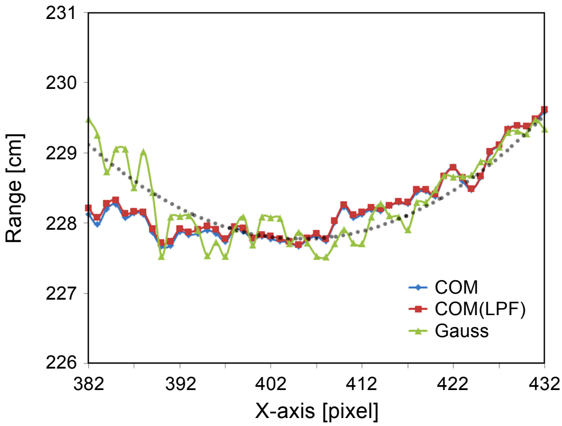

Fig. 9. Comparison of range profiles acquired from a tube surface in backscattering foggy environments.

were thresholded by 30. The window size used for the Gaussian correlation signal in "Gauss" was 21. As shown in Fig. 8, the displayed range resolution is not visually distinguishable among the images due to the limitation of grayscale normalization of 8-bit. To assess the range resolution in detail, an average of three lines ((382, 259)–(432, 259), (382, 260)–(432, 260), (382, 261)–(432, 261)) on the dotted line of Fig. 7 was selected, as shown in Fig. 9. Here, the signal notations are the same as in Fig. 5 and "COM(LPF)" also uses the zero-phase LPF of a 1 × 11 window. The dotted line is the range profile on the target surface. Also, the window size (N_s) to extract the COM position from the peak area in the "Gauss" was 1 × 11. As shown by the results in Fig. 9, the "Gauss" provides more precise range information than the conventional techniques "COM" and "COM(LPF)". The range errors of the conventional techniques "COM" and "COM(LPF)" are relatively high on the left side compared to the right side because of the relatively lower signal-to-noise ratio. As we can also see here, the LPF signal is not effective against the backscattering bias noise because the biasing error is not reduced.

Pixel profiles ("X40", "X387", "X420") of range-gated images at the (x, y) positions of (40, 260), (387, 260) and (420, 260) are shown in Fig. 10. Here, "X387" and

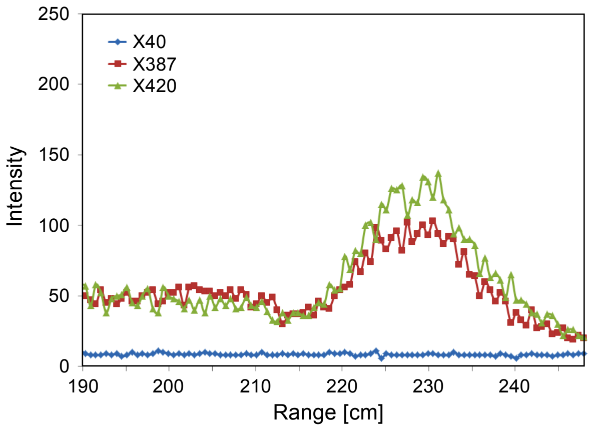

Fig. 10. Comparison of intensity profiles of range-gated images in different reflection positions.

“X420” are the left side and the right side of the target surface and “X40” is a signal in the case of a dark background. We can see that the effect of the backscattering bias noise in signal-to-noise ratio is relatively high on the left side because the reflection ratio from the left side is lower. As shown in Figs. 9 and 10, although the lower reflection ratio decreases the range resolution of the conventional measuring techniques, the “Gauss” method efficiently reduces the bias noise effect. The range information was extracted from the line profile having the highest intensity values composed of 47 data, as shown in Figs. 11 and 12. The intensity profile signal was thresholded by 30 and the delaying step Δd was 0.6 cm. Two profile samples from the positions (387, 260) and (420, 260) are shown in Figs. 11 and 12, respectively. We can see the high intensity drift of the illumination pulse laser from the range-gated pixel intensity of “COM”.

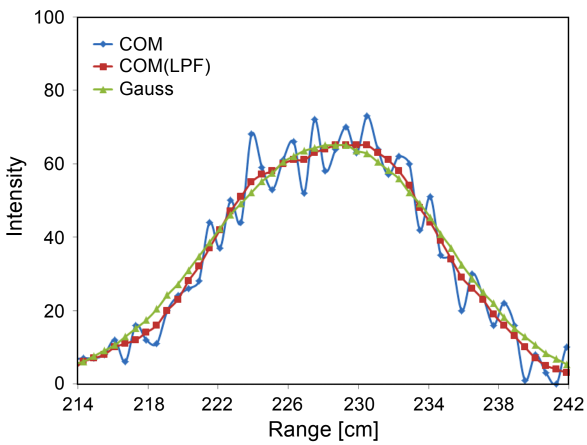

Fig. 11. Comparison of range positions extracted from a low reflection position.

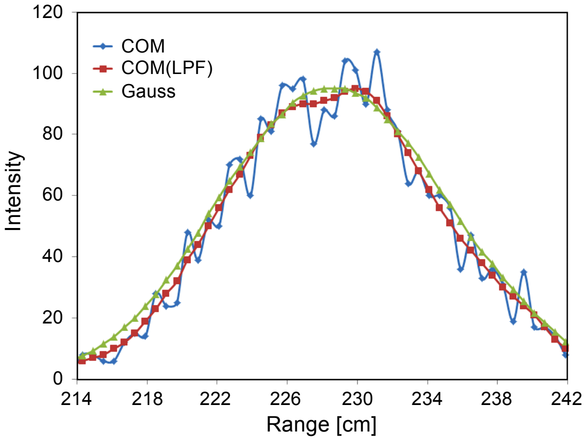

Fig. 12. Comparison of range positions extracted from a high reflection position.

Here, the signal is not an averaged signal. The signal of "COM(LPF)" is a smoothed profile using an averaging filter of a 1 × 11 window for the raw range-gated signal of "COM" and the signal of "Gauss" is a cross-correlated signal of the raw range-gated signal and a Gaussian window of 1 × 21. When the target range position was 228.6 cm, the measured range positions of "COM", "COM(LPF)" and "Gauss" were 228.1, 228.1, and 228.5 cm, respectively, as presented in Fig. 11. The corresponding values of Fig. 12 were all 228.6 cm when the target position was 228.3 cm. We can see that the range values measured from the conventional measuring techniques using the COM position are biased to the left by the backscattering noise of airborne fog particles whereas the proposed technique provides robust and precise range information in the backscattering foggy environment.

4. Conclusion

In this paper, a short-range imaging technique that is useful in highly backscattering noise environments is proposed for an active range-gated vision system to monitor hazy targets. A windowed center-of-mass position measured from the peak area of a cross-correlation signal of two signals, a range-gated profile according to the range direction and a Gaussian window signal in reduced size, is adopted as the range depth. A range-gated active vision system is configured and evaluated through experiments to visualize non-visible hazy targets. The system efficiently measured 2D and range images for hazy metal tube targets. From the experimental results, the proposed measuring technique provided more precise range information than the widely used conventional techniques based on the center-of-mass position in an airborne foggy environment. We demonstrate that the fast measuring technique is efficient for monitoring targets of a range-gated vision system, especially in backscattering foggy environments.

References

[1] DONATI S., SONA A., *Evaluation of visibility improvement in fog by the range gating technique*, Opto-electronics **1**(2), 1969, pp. 89–101.

[2] BELIN E., CHRISTNACHER F., TAILLADE F., LAURENZIS M., *Display of an analytical model for backscattered luminance and a full-field range gated imaging system for vision in fog*, Proceedings of SPIE **7088**, 2008, article ID 70880O.

[3] LAURENZIS M., CHRISTNACHER F., BACHER E., METZGER N., SCHERTZER S., SCHOLZ T., *New approaches of three-dimensional range-gated imaging in scattering environments*, Proceedings of SPIE **8186**, 2011, article ID 818603.

[4] FOURNIER G., BONNIER D., FORAND J.L., PACE P., *Range-gated underwater laser imaging system*, Optical Engineering **32**(9), 1993, pp. 2185–2190.

[5] WEIDEMANN A., FOURNIER G.R., FORAND L., MATHIEU P., *In harbor underwater threat detection/identification using active imaging*, Proceedings of SPIE **5780**, 2005, pp. 59–70.

[6] SLUZEK A., TAN CHING SEONG, *Novel results in short-range visualization and vision systems based on gated imaging*, 6th Conference on Applied Electromagnetics, Wireless and Optical Communications, Trondheim, Norway, July 2008, pp. 21–27.

[7] XIUDA ZHANG, HUIMIN YAN, JINLIANG YAO, WANGPIN SHANGGUAN, *Exponential increase partitions method for three-dimensional active imaging*, Proceedings of SPIE **7506**, 2009, article ID 75062Q.

[8] GILLESPIE L.F., *Apparent illuminance as a function of range in gated, laser night-viewing systems*, Journal of the Optical Society of America **56**(7), 1966, pp. 883–887.

[9] LAURENZIS M., CHRISTNACHER F., MONNIN D., *Long-range three-dimensional active imaging with superresolution depth mapping*, Optics Letters **32**(21), 2007, pp. 3146–3148.

[10] ZHANG XIUDA, YAN HUIMIN, JIANG YANBING, *Pulse-shape-free method for long-range three-dimensional active imaging with high linear accuracy*, Optics Letters **33**(11), 2008, pp. 1219–1221.

[11] ANDERSSON P., *Long-range three-dimensional imaging using range-gated laser radar images*, Optical Engineering **45**(3), 2006, article ID 034301.

[12] GÖHLER B., LUTZMANN P., *Experimental comparison of a gated-viewing system and a 3-D flash LADAR system in terms of range precision under different turbulence conditions*, SENSOR+TEST Conferences 2011 – IRS^2 Proceedings, 2011, pp. 145–150.

[13] ANDERSEN J.F., BUSCK J., HEISELBERG H., *Pulsed raman fiber laser and multispectral imaging in three dimensions*, Applied Optics **45**(24), 2006, pp. 6198–6204.

[14] BUSCK J., HEISELBERG H., *Gated viewing and high-accuracy three-dimensional laser radar*, Applied Optics **43**(24), 2004, pp. 4705–4710.

[15] BUSCK J., *Underwater 3-D optical imaging with a gated viewing laser radar*, Optical Engineering **44**(11), 116001, 2005.

[16] CHUA S.Y., WANG X., GUO N., TAN C.S., CHAI T.Y., SEET G.L., *Improving three-dimensional (3D) range gated reconstruction through time-of-flight (TOF) imaging analysis*, Journal of the European Optical Society-Rapid Publications **11**, 2016, article ID 16015.

[17] SING YEE CHUA, XIN WANG, NINGQUN GUO, CHING SEONG TAN, *Range compensation for accurate 3D imaging system*, Applied Optics **55**(1), 2016, pp. 153–158.

[18] SALMAN S.A., KHALEL J.M., *Attenuation of infrared laser beam propagation in the atmosphere*, Diala Journal **36**, 2009, pp. 29–36.

[19] LAURENZIS M., CHRISTNACHER F., MONNIN D., ZIELENSKI I., *3D range-gated imaging in scattering environments*, Proceedings of SPIE **7684**, 2010, article ID 768406.

Received October 25, 2016
in revised form February 15, 2017