Smartphone background-oriented schlieren for locating gas-leak source in emergencies

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ABSTRACT

We propose a smartphone background-oriented schlieren (SBOS) technique, which is inexpensive, and easy to implement for gas-leak detection due to density field variations in the air. Traditional gas-leak detectors are often designed to measures point-wise concentration in the gas-filled space and thus not suitable for immediate location of leak source. SBOS is proposed as an alternative method for gas-leakage detection safely and quickly since SBOS optically measures the density changes without direct non-contact. The smartphone as a portable gas leak detector has significant advantages compared to the high-speed camera often used in laboratory research since it is inexpensive and portable. We apply SBOS to measure the density gradient field of the air around a flame and helium gas jetting from a nozzle at high-pressure. In order to detect the density gradient by SBOS, we use only a smartphone as BOS camera, a room lamp as light source and a color background. In the analysis we use the colored-cross-correlation method which reduces noises of displacement fields. First, as a proof-of-concept, we experimentally obtain a series of local displacement field by using SBOS. The apparent density gradient by the helium gas jet is confirmed in both the one-shot mode (3,024×4,032 pixels) and the slow-motion mode (1,280×720 pixels, 240 fps). These results indicate that SBOS is able to detect the local displacement related to density gradient changes in the air. Second, to validate the measurement results using a smartphone, we compare the results with those using a high-speed camera often used in laboratory research. The magnitude of the displacements obtained by the two cameras also show a reasonable agreement. These results suggest that SBOS has sufficient potential to detect density gradients, for the gas leak detection applications. This technique is considered to be useful for various density fields such as the sound wave field in the air. We will investigate the performance of SBOS as a gas-detector for fast gas leak source detection.

1. Introduction

Propane gas is indispensable for manufacturing industry and home cooking. Although providing gas by piping is a common industrial method, several cases of gas-leak are reported (Murvay et. al., 2012). A gas leakage is detected by using a sensor fixed at a certain location (e.g. fire-alarm box at home) or a mobile gas-detector (e.g. combustible gas-detector). A fixed gas sensor can monitor the gas concentration. But traditional gas detectors are often designed to measure point-wise concentration in a gas-filled volume and thus not suitable for immediate location of leak source. When the gas leakage occurs, a repairman or a fireman having a mobile gas-detector must find a gas leak source in dangerous area filled with combustible gas. In order to detect the location of the leak source at any as quickly as possible, non-contact measurement of density fields with a portable device is necessary.

The background-oriented schlieren (BOS) which is a non-contact measurement method for density field variation may provide a solution. BOS can measure optically the density gradient field using only a smartphone camera, a light source and a background (e.g. printed random-pattern) (Richard et al., 2001, Raffel et al., 2015). By comparing a background image disturbed by density gradient and a non-disturbed background image, the local displacement due to the density gradient is obtained. In general BOS is applied for fluid or thermal measurements such as the shock wave in the air (Venkatakrishnan et al., 2004, Kirmse et al., 2011), the underwater shock wave (Yamamoto et al., 2015, Hayasaka et al., 2016), compressed flow (Tan et al., 2015), flame in the air (Richard et al., 2001). However, BOS cameras used in these studies have high spatial resolution, recording speeds and sensitivity for laboratory experiments. Thus, it is expensive and not suitable for carrying.

Here, for the first time we propose BOS using a smartphone (Smartphone BOS; SBOS) as a new inexpensive gas leak detector for gas-leak source tracking in emergencies. Recently, a smartphone is of great interest as an experimental camera (Chen et al., 2017, Marshall et al., 2017, Cierpka et al., 2016, Aguirre-Pablo et al., 2017) since the performance of smartphone is rapidly improving. To the best of the authors' knowledge, using a smartphone as BOS camera has not been conducted.

In this paper we apply SBOS to measure experimentally the density gradient field of helium gas jetting from a nozzle of high-pressure container as a proof-of-concept. In the analysis we use the colored-BOS technique (Leopold et al., 2013) which reduces noises of displacement fields. To validate the results using a smartphone, we compare the measurements with those using a high-speed camera often used in laboratory research.

2. BOS technique

We present the principle of BOS in Fig.1 (van Hinsberg and Rösgen 2014, Hayasaka et al., 2016). It consists of a camera and a background of a random generated dot pattern. The BOS compares a "non-disturbed" background image and a "disturbed" background image due to the presence of the density gradient. The ray disturbed by the density gradient is indicated by the red line in Fig.1. The BOS then considers the displacement v', which is related to the integral of the density gradient as (van Hinsberg and Rösgen 2014, Hayasaka et al., 2016),

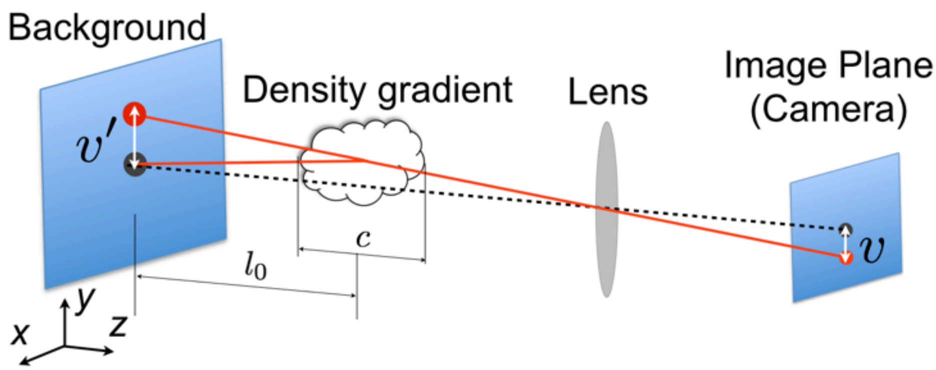

Fig.1 Principle of BOS technique.

$$\boldsymbol{v}' = \frac{1}{2}c(c+2l_0)\frac{1}{n_0}\nabla n, \qquad (1)$$

where c is the thickness of the density gradient, l_0 is the distance from the background to the density gradient, n is the refractive index, n_0 is the refractive index of the air and ∇ is the gradient operator on the coordinate plane (x, y). The relationship of the refractive index n and the density ρ is written with the Gladstone-Dale constant K (Merzkirch, 2012) as,

$$n = K\rho + 1. \qquad (2)$$

Substitution of Eqs. (2) into (1) yields

$$\boldsymbol{v}' = \frac{1}{2}c(c+2l_0)\frac{K}{1+K\rho_0}\nabla\rho. \qquad (3)$$

Note that the displacement vector $\boldsymbol{v}'$ obtained by the BOS technique is the path-integrated quantity across the measurement domain with the density gradient. The local displacement $\boldsymbol{v}'$ is obtained by cross-correlation method.

3. Experimental setup

Fig.3 (i) and (ii) show a sketch and a photograph of the experimental setup, respectively. We measure the helium gas jet or the flame from a lighter as a source of density gradient. The helium gas compressed in a container (0.93MPa, 20°C) is jetted from a nozzle. We use a room lamp for illumination. The density gradient is captured using a smartphone (iPhone8, Apple Inc.) with 240 fps and 1,920×1,080 pixels in color. The shutter speed and the ISO are adjusted automatically by the smartphone. The color background with random-dot pattern (spatial resolution: $3\times3\text{mm}^2/\text{pixels}$) is placed behind the density gradient. The distance from the background to the camera is one meter. To compare the local displacements obtained with a smartphone and those with a high-speed camera (FASTCAM SA-Z (Color), Photron Ltd., 250 fps, 1,024×1,024 pixels),

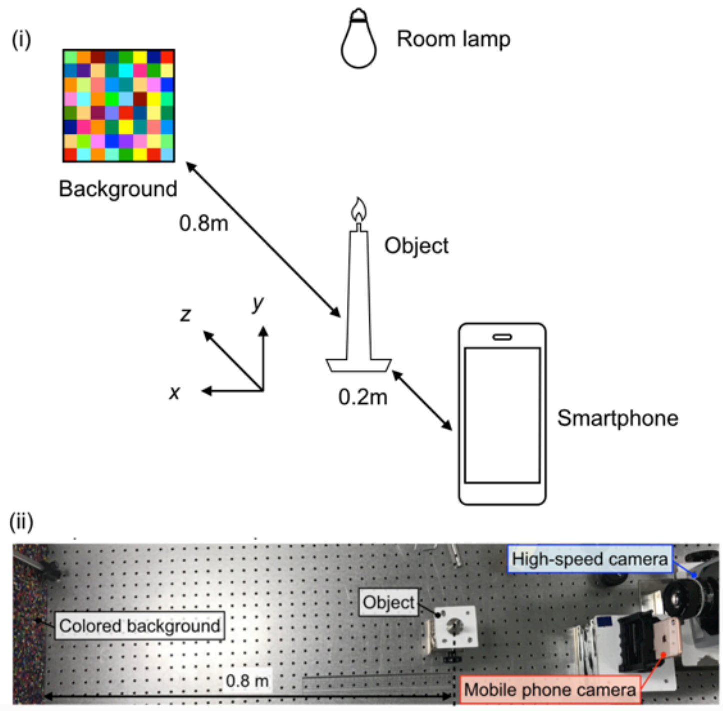

Fig.2 (i) A schematic of experimental setup. (ii) a photo from above.

we place two cameras at the similar location. A single lens (AF-S NIKKOR 50mm f/1.8G) is installed in a high-speed camera.

4. Image analysis

When the color camera (smartphone) and a colored-background plate are used, we can apply a colored-cross-correlation method. Fig.2 shows the procedure of image analysis to obtain the local displacement v' processed by Matlab code. After recordings, we have a reference image (a background image without density gradient) and disturbed images (background images with density gradient, e.g. flame) (Step1). The image registration based on the affine transformation (Hayasaka et al., 2016) is applied to all images (Step2) for the preparation of the cross-correlation calculation in the next step (Step3). Then we use the color-cross-correlation method to obtain the displacement fields (Leopold et al., 2013) to reduce the measurement error. An original color image is separated into four color images (Red, Green, Blue, Gray) based on the intensity of RGB value. Then we analyze each color image with cross-correlation method, FFT algorithm [50 % over-lap with the Fast Fourier Transform (FFT) multi-pass interrogation (from 64 to 4 pixel)] using PIV lab 1.4 (Thielicke et al., 2014) (Step3). Finally, the averaged-displacement field is obtained from the four displacement fields (Step4).

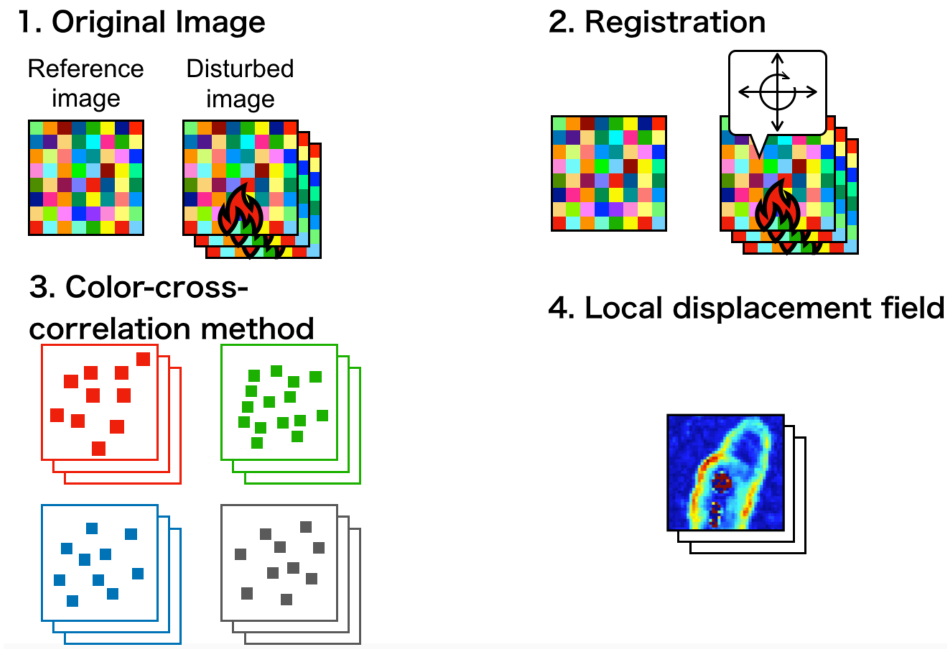

Fig. 3 Procedure of image analysis.

5. Result and Discussion

5.1 Proof-of-concept

Results of a proof-of-concept experiment using SBOS is shown in Fig4(i), (ii) and (iii) which display the original image taken with the smartphone, the local displacement field (vector) of the helium jet and the local displacement field (magnitude), respectively. Fig.4 is photographed by one-shot mode (3,024×4,032 pixels). This result confirms the density gradient by helium gas jet, which suggests that SBOS technique is able to detect a density gradient related to density and temperature in the air.

A temporal sequence of local displacements obtained by the helium jet is shown in Fig.5 which is photographed using the slow-motion mode of the smartphone (1,280×720 pixels, 240 fps). We compare the density estimated by the ideal gas low to the one obtained by SBOS. By using the Gladstone-Dale equation (Eq.2), the refractive index of helium gas in the tip of a nozzle is estimated theoretically to n = 1.3 when the density of helium gas in a container is 1.6 kg/m^3. Based on the local displacement obtained by SBOS, the density is estimated the 1.5 kg/m^3 using Eq.3 (c = 10 mm, l_0 = 1 m, v' = 1 pixel). This result indicates that we have successfully measured the displacement field obtained by the gas flow from a high-pressure container, resembling gas-leak source.

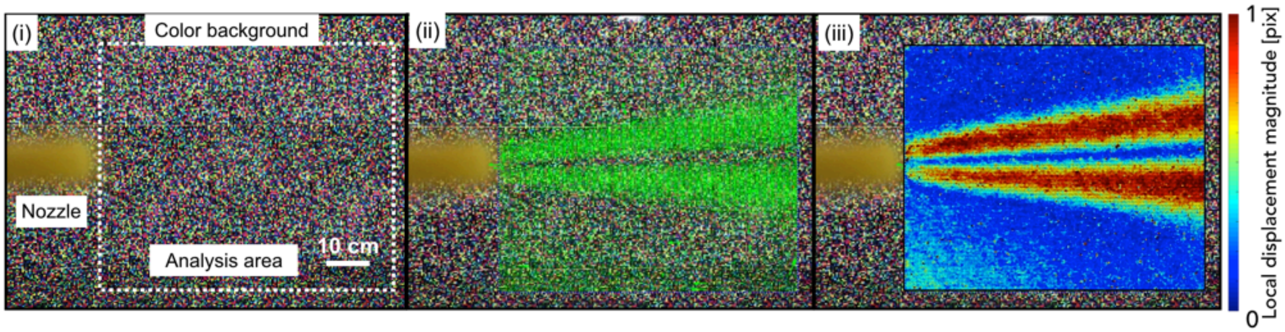

Fig.4 Demonstration of SBOS with the helium gas jet. (i) Original image. The area indicated by the white dot line is analyzed by cross-correlation method. (ii) The local displacement (vector). (iii) The local displacement (magnitude).

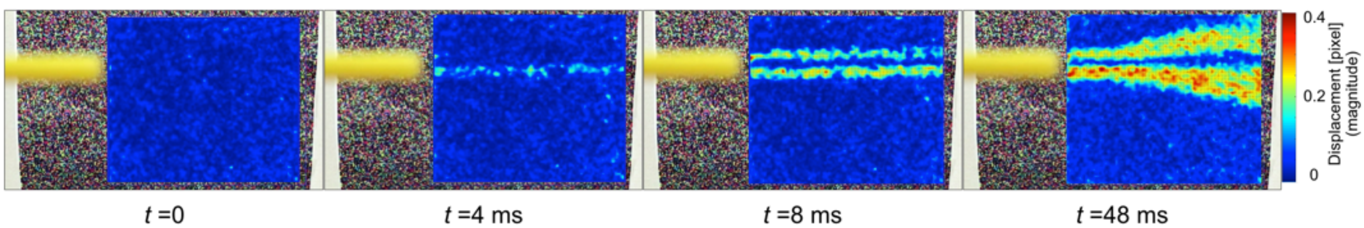

Fig.5 The series of local displacement (magnitude) by the jet from helium gas. The jet flows from left to right.

5.2 SBOS comparison between smartphone and high-speed camera

For further consideration, we compare results using the smartphone with that using the high-speed camera. Fig.6 (i) shows the original image captured by the smartphone (1,280×720 pixels, 240 fps) where the digital zoom is applied. Fig.6 (ii) shows the local displacement vector field. Fig.6 (iii) shows the original image captured by the high-speed camera (1,024×1,024 pixels, 250 fps) and Fig.6 (iv) shows the local displacement vector field. The comparison reveals that an image captured by the high-speed camera is clearer than that the one obtained by the smartphone.

Fig.7 (i) displays both the displacement field of Fig. 6(ii) and Fig. 6(iv) where the red vector and the blue vector represent the local displacement obtained by the smartphone and the high-speed camera, respectively. These distributions of local displacement fields are found in good agreement considering the limited sensitivity of the smartphone in comparison with a high-speed camera. Fig.7 (ii), (iii), (iv) show the magnitude of displacements obtained by the two cameras on the horizontal lines indicated in Fig. 7 (i), also showing a reasonable agreement. The deviation might be due to the distortion of a 28mm wide-angle lens of the smartphone where a wide-angle lens is known to provoke radial distortion on the object image. A single-lens attached to the high-speed camera provides a less distorted image. Secondly, the deviation might be due to the effect of digital zoom in the smartphone. The digital zoom affects the image quality caused by image interpolation. For further validation, we will compare the refractive indices between SBOS and theoretical value.

6. Conclusion

We propose a smartphone background-oriented schlieren (SBOS) technique, which is inexpensive, and easily detects the density fields in the air. We apply SBOS to measure the density gradient field of the helium gas jet. First, we obtain a series of local displacement field using SBOS and the result suggests that SBOS has potential to detect density gradients, applicable for the gas leak detection. Second, we compare the profile of local displacement fields obtained using the smartphone with those using the high-speed camera. Both distributions of local displacement fields are found in good qualitative agreement. In the future work we will validate the refractive index or density gradient between SBOS and theoretical value. Furthermore, we will investigate the performance of SBOS as a fast gas-detector for localizing gas leak sources.

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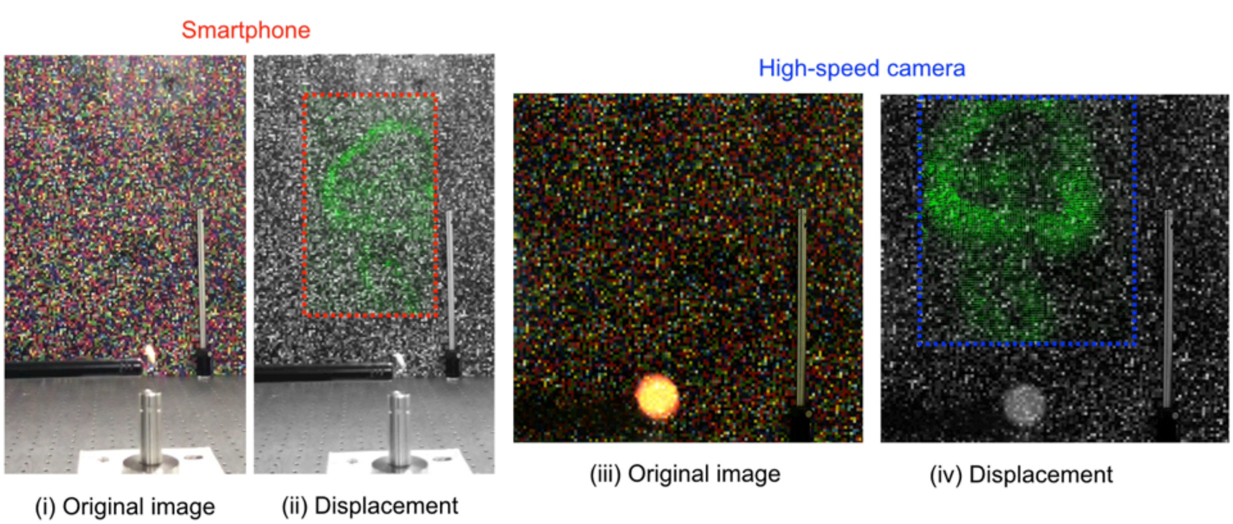

Fig. 6 Photographs of a flame shot by (i) a smartphone and (iii) a high-speed camera. (ii) and (iv) display the local displacement vector fields calculated from (i) and (iii), respectively. Cross-correlation method analyzes an area surrounded by a dot line.

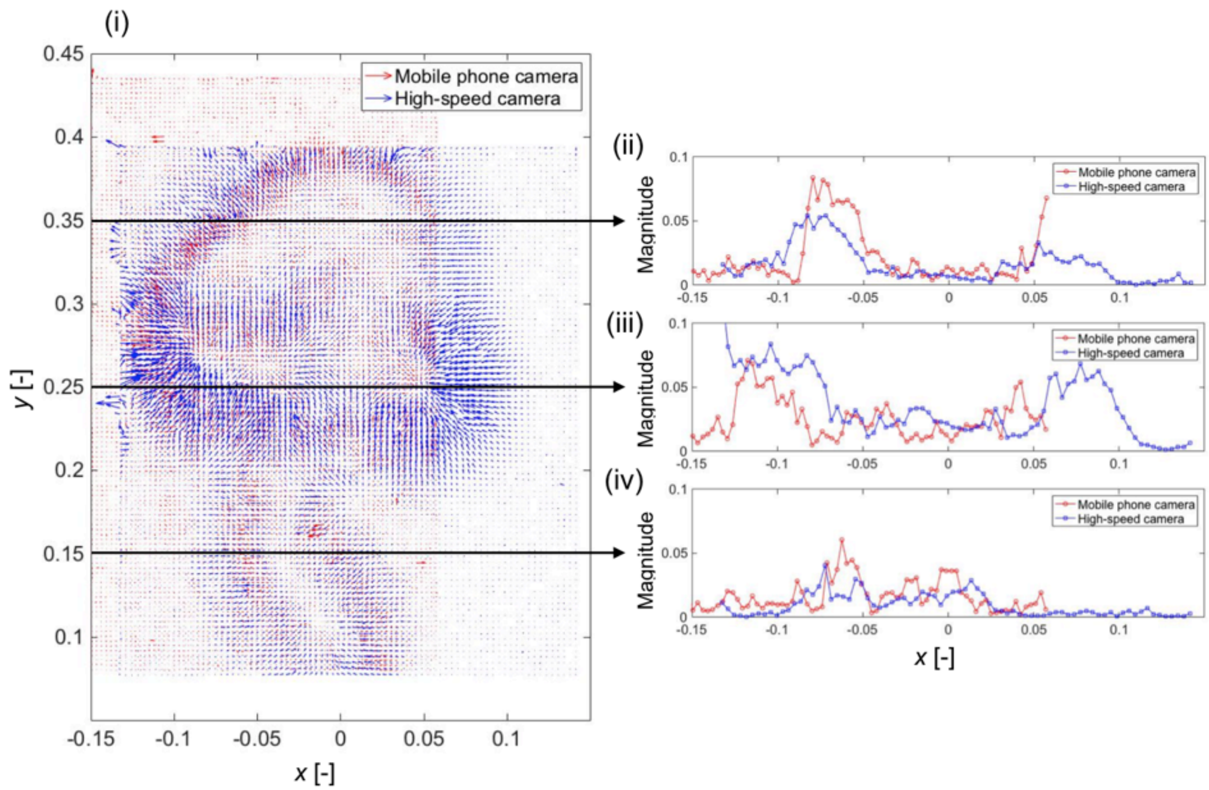

Fig.7 Comparison of local displacement fields obtained by a smartphone (analysis from Fig.5 (ii)) and a high-speed camera (obtained from Fig.5 (iv)). Fig.6 (ii), (iii), (iv) represent the magnitude of local displacement on horizontal lines indicated in Fig.6 (i).

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