Analysis of the Smartphone Camera Exposure Effect on Laser Extraction

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Abstract— In this study, we investigate the effect of smartphone camera exposure on laser extraction performance in a digital image. The laser extraction is the most crucial operation in laser triangulation systems that obtain object measurements from the projected laser light captured in the image. The exposure settings consist of sensor sensitivity (ISO), aperture, and shutter speed. This study provides insight into the smartphone settings and the exposure adjustment for further complicated laser extraction. A smartphone camera (Apple iPhone 11) and a laser stripe projector operating at 405 nm were employed. Analysis of different ISO values, the effect of aperture and shutter speed on the laser extraction quality was performed.

Keywords—camera exposure; image processing; laser extraction

I. INTRODUCTION

Due to the continuing and rapid advances of both hardware and software technologies in smartphones and cameras, we continue to have access to cheaper, faster, and higher quality and smaller cameras and computing units. Smartphones have been equipped with built-in complementary metal-oxide-semiconductor (CMOS) cameras [1]. These CMOS cameras can capture high-resolution videos with a resolution of at least 1920×1080 pixels and a capture rate of 30 fps. Due to the large scale and increasing availability of smartphones, smartphone camera-based laser triangulation systems has become an attractive option for vision-based measurement [2-5]. These smartphones also have a high sufficient processing unit that allows image processing and computational intelligence to be implemented more easily and affordably. Furthermore, internal memory and communication networks (WIFI and Bluetooth) can store and transfer measuring results across different external storage locations.

A laser triangulation system (LTS) consists of a laser projector and camera. A laser line is projected onto the target surface at an angle, and a series of frames containing laser information are embedded in intensity and spatial coordinates, which is the most critical factor contributing to the overall effectiveness of laser extraction. The smartphone-based LTS utilizes a smartphone CMOS camera as the laser detector and has an inherent advantage of capturing data in 2-dimensions (2D). Hence, the camera exposure settings for focusing on capturing data is essential.

In this work, we study the effect of camera exposure, including image sensor sensitivity (ISO), aperture, and shutter speed. A laser module of 405 nm wavelength and an Apple iPhone 11 are used as the transmitter and the receiver, restrictively. Experiments are performed by changing the ISO and shutter speed on the commonly used resolution of full-HD (FHD) (1920×1080). The effect of shutter speed and different ISO values on the link performance are investigated. We show quantitative results as SNR values and subjective results as laser extraction.

The rest of the paper is organized as follows. Section 2 describes the smartphone camera's exposure settings for laser extraction. Section 3 shows the experimental setup and discussion, and Section 4 presents the conclusions of this study.

II. SMARTPHONE CAMERA-BASED LTS

A. Exposure Triangle for Camera Capturing

The camera's exposure is calculated by combining the lens aperture, image sensor sensitivity (or ISO), and shutter speed, as shown in Fig. 1. As explained in [6, 7], the lens aperture controls the amount of light being captured through the lens and controls the depth of field, which is the portion of a scene that appears to be sharp. For a small aperture, the depth of field is small, while for a large aperture, the depth of field is small. In photography, the aperture is expressed by F-number (focal ratio), representing the ratio of the lens's diameter aperture to the length of the lens. A camera's shutter speed is typically measured in fractions of a second. Slow shutter speeds allow more light incidents and are used for low-light and night photography, while fast shutter speeds help freeze motion. Higher ISO (i.e., the camera's sensitivity) means faster light absorbed by the sensor, but at the cost of the increased noise level.

$$I(x,y) \propto N \times t \times S \tag{1}$$

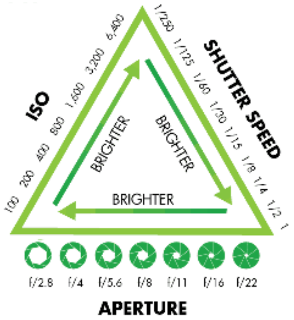


Fig 1: Camera exposure triangle (image inspired by [7])

The brightness, or intensity, of each pixel in the image is mainly determined in Equation (1). The image is said to be overexposed (too bright/no details) when too much light is captured. On the other hand, the image is underexposed (dark/grainy/fewer details) if less light is captured. The overexposed effect means that the number of photons reaching the image sensor exceeds its maximum capacity. The excess photos will be either spill or merge into adjacent pixels, thus leading to non-precise intensities [8]. The leftmost images in Fig. 4 illustrated this problem.

B. Camera-based LTS

Smartphone camera sensor. In this study, an Apple iPhone 11 smartphone's wide-angle camera is utilized in the proposed smartphone camera-based LTS. The camera is a 12-megapixel CMOS sensor with a focal length of 26 mm (in 35 mm format equivalent) and a fixed aperture value of F1.8. The camera has a shutter speed in the range of 1/24000 s to 1 s and ISO of 32 (low ISO) to 3072 (high ISO). The resolutions supported by the wide-angle rear camera are listed in Table 1. All values are extracted using the AVFoundation framework in iOS.

Laser triangulation setup. Laser triangulation is an image processing technique used to capture 3D measurements of the object by combining a laser illumination source and a camera sensor. Fig. 2 shows the reverse geometry setup where a laser stripe projector is positioned at an angle $\alpha = 45°$ to the object surface. At the same time, a camera detects scattered light facing perpendicular to the surface. An image of the laser line is formed, from which the laser profile $Z(X)$ can be computed through trigonometric relations. This setup's advantage is that any small change in the object height produces a massive shift in the laser line position, making it better for measuring high accuracy depth. The depth-sensing range ΔZ and can be calculated as:

$$Z_{min} = \frac{b\cos\alpha\cos\frac{\theta}{2}}{\cos\left(\alpha - \frac{\theta}{2}\right)} \quad Z_{max} = \frac{b\cos\alpha\cos\frac{\theta}{2}}{\cos\left(\alpha + \frac{\theta}{2}\right)} \tag{2}$$
$$\Delta Z = Z_{max} - Z_{min}$$

All characteristics of the LTS in this study are summarized in Table 1.

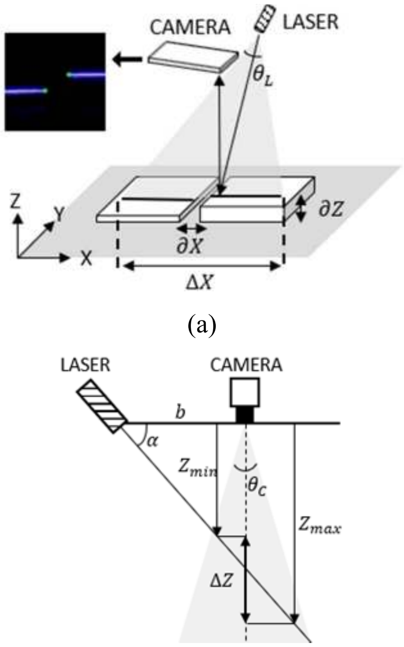
Laser extraction. The laser extraction algorithm comprises image processing operations aimed at precisely locating the laser peaks' sub-pixel position in the image. First, the blue channel is extracted from the RGB image obtained from the camera since the laser is operating in the violet-blue region (405 nm wavelength). Fig. 3a represents the blue channel with the pixel's grayscale value at the i^{th} row and j^{th} column, denoted by $I(i,j)$. The image is then preprocessed with median filtering to remove noise-and-pepper noise. The median filtering with a window size of 3×3 is a low-cost and effective smoothing technique to remove noise while preserving edges, as previously demonstrated in [9]. The results obtained after this step is illustrated in Fig. 3b.

Second, the CoMP technique [10] is implemented to extract the laser line's center position per column at sub-pixel accuracy. The location of the peak intensity in each column j can be computed by:

$$comp_j = i \times \sum_{i=L}^{U} I(i,j) \bigg/ \sum_{i=L}^{U} I(i,j) \tag{3}$$

where the lower bound L and the upper bound U determine the scanning interval and are calculated by:

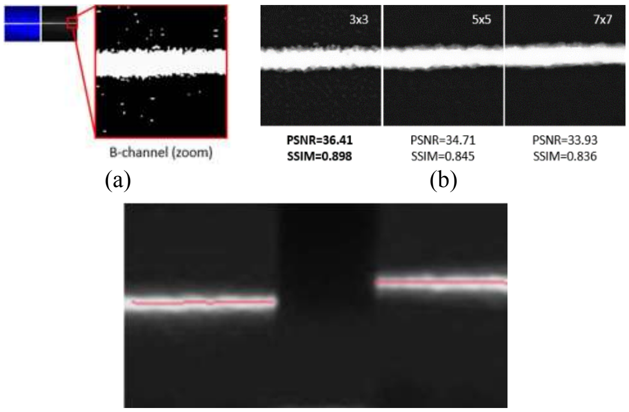
$$\begin{aligned} L_j &= I(max, j) - 0.5s \\ U_j &= I(max, j) + 0.5s \end{aligned} \tag{4}$$



(a)

(b)

Fig 2: a) Reverse geometry triangulation setup. b) Sensing range.



(a) (b)

(c)

Fig 3: a) Visualizing the Gaussian profiles of the 405 nm laser line. b) Median filter results using different window sizes. c) Illustrating the extracted laser stripe center.

The scanning interval varies for each column depending on the row index of the peak value

$$I(max, j) = \arg\max_{i}\big(I(i, j)\big) \tag{5}$$

The value of s controls the scanning interval conforming to the Gaussian distribution of the laser intensity, which ranges from several pixels to tens of pixels. From the experiments, $s = 21$ is chosen to accommodate the spread of the laser line. Examples of laser extraction are shown in Fig. 3c.

III. EXPERIMENT AND DISCUSSION

A. Experimental Setup

Fig. 4 shows the experiment setup, which was used to investigate the effect of camera exposure settings on laser extraction performance. The laser stripe projector is a 20 mW violet-blue 405 nm type. As previously mentioned, the wide-angle rear camera of the Apple iPhone 11 was used. Because of the triangulation setup, the standoff distance between the camera and the measured object is short, around 110 mm. Table 1 shows the system parameters used to perform the experiments.

B. Results and Discussion

Images were captured by changing the ISO values from 32 to 3072 with FHD resolution (1920×1080). The shutter speed values were also changed from 1 s to 1/24000 s.

Since the ISO sensitivity (S) controls the sensor's light absorption rate, reducing this value by half means that double the amount of light is required to produce the same image brightness. Hence, a low ISO value results in darker images and less noise. At a short standoff distance, a laser pulsing at 20 mW and a shorter camera exposure help overcome ambient light interference.

As the shutter speed increases from 1/24000 s to 1/1 s, the blooming effect can be seen in Fig. 4. This is because increasing the shutter speed a higher time of light passing through the camera lens, thus increasing incoming photons. The photons start to spread and merge with the photons on the adjacent pixels causing the blooming effect, as seen in Fig. 4.

TABLE 1: LTS Characteristics

Component	**Characteristics**
Camera sensor	12-megapixel CMOS sensor, physical sensor size 1/2.55" (6.17×4.55 mm), image resolution 4032×3024, frame rate 60 fps. Wide-angle with focal length 26 mm (in 35 mm format equivalent), numerical aperture $N = f1.8$, shutter speed $t = 1/24000 - 1/1\,s$, ISO $S = 32 - 3072$, $\theta_C = 65.6$
Laser projector	Laser diode generator, $\lambda = 405$ nm (violet-blue), 20 mW, input voltage 3-5 V, class II
Triangulation setup	Baseline $b = 65$ mm, triangulation angle $\alpha = 45°$, standoff distance 110 mm, depth-sensing range $\Delta Z = 143.3$ mm, horizontal sensing range $\Delta X = 68.1$ mm

In a real-world application, instead of manually manipulating ISO and shutter speed, the exposure bias can be adjusted. The exposure bias is a high-level API provided by the AVFoundation framework in iOS to automatically adjusts the ISO and shutter speed to achieve the desired brightness in the image. The exposure bias is subsequently decreased (0.0 by default) until a thin laser line appears in the image. When the laser line's width is smaller than a threshold (21 in our experiments), the adjustment process is completed. Fig. 4 shows that an exposure bias value of -3.0 produces the best results in both white and black colors. This algorithm provides good rejection of indoor ambient noise and localizes the laser line peak in the image.

Fig. 5 shows the per-frame total processing time of the laser extraction algorithm versus image resolution. The camera can capture frames at a rate of 60 fps. To achieve real-time processing speed, each frame needs to be processed below 16.66 ms. At 1920×1080 resolution, the CPU usage is around 79% and the

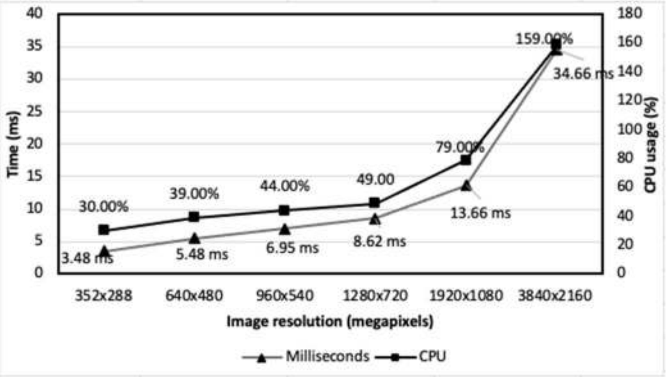


Fig. 5: Processing time per frame and CPU usage by the laser extraction algorithm versus image resolution

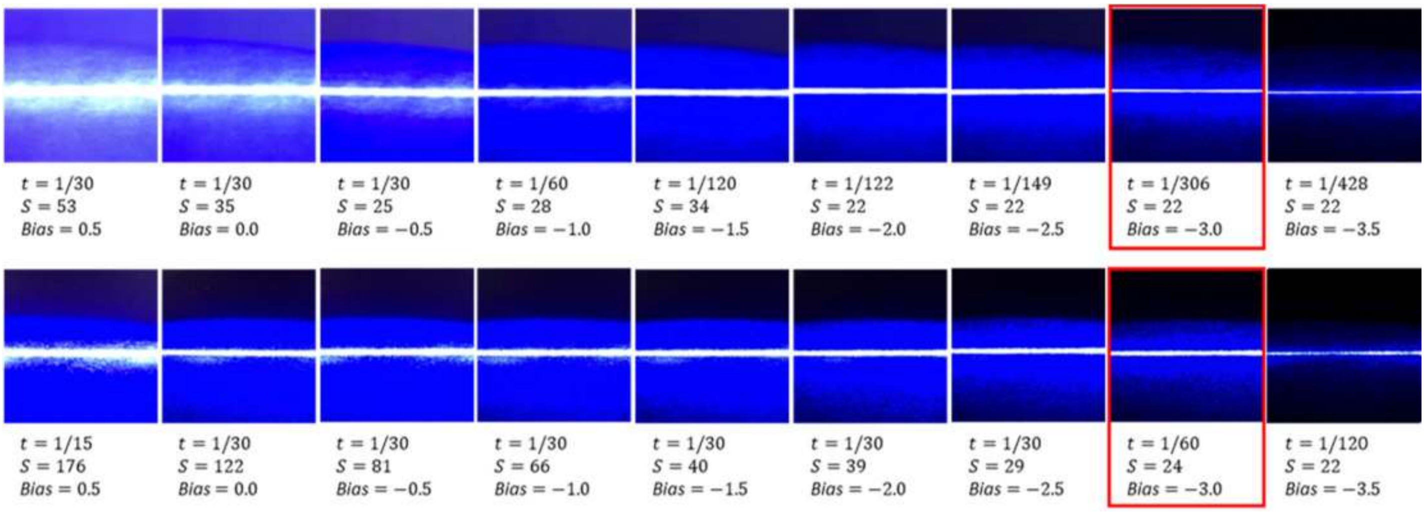


Fig. 4: Illustration of the effect of different exposure settings on 405 nm laser light. First row: testing on a white surface. Second row: testing on a black surface. The best exposure setting is marked in red (best view in color).

processing time for each frame is 13.66 ms. Therefore, we capture images at 1920×1080, optimizing computational cost, and CPU usage within the smartphone's compute performance limits.

IV. CONCLUSION

A study on the effect of smartphone camera exposure settings on laser extraction was performed using an Apple iPhone 11. The experimental results demonstrated that the higher ISOs and higher shutter speed increase the camera's sensitivity to absorb light faster and therefore experienced more noise. Using an exposure bias value of -3.0 gives the best laser capturing in both white and black surface colors. Also, at the FHD image resolution, the computing cost and CPU usage can be optimized. This study shows the smartphone camera sensor's capability in developing portable laser triangulation systems for object measurement. The study can be further extended to complex analysis of exposure settings on the performance of laser extraction with different wavelengths such as green (520 nm), red (650 nm), ir (980 nm), etc.

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