Guidelines for Optimizing Optical System Design for Laser Speckle Authentication

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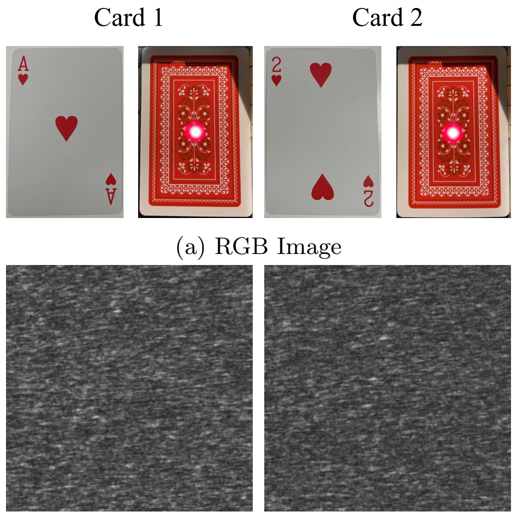
Abstract

This study examines the optimal optical system design for object authentication using laser speckle and clarifies the constraints of each parameter. The previous study did not address the optimal optical system design and was limited to ad-hoc, individual optimizations such as designing fixtures to fix the target object to ensure robustness against positional displacement, or devising pattern matching algorithms. This study reveals the relationship between the pixel size and the average speckle size, which can be used as a feature for individual identification, providing guidelines for the optimal optical system design for laser speckle authentication. Furthermore, we demonstrated that an optical system designed according to our proposed guidelines enhances robustness against translation.

1 Introduction

Artifact metrics are techniques for identifying and authenticating individual objects by sensing their unique surface features, without attaching explicit tags, like barcodes. These applications are such as anticounterfeiting and traceability in manufacturing environments [1]. One approach captures surface microstructures as "object fingerprints," which are then matched using image processing. Guidelines such as the FIBAR method have been proposed to help design optical systems that capture these fingerprints clearly, offering versatility across diverse objects [2]. However, these systems can be vulnerable to environmental conditions, such as lighting. Size and cost constraints further limit practical deployment.

In contrast, laser speckle patterns produced by coherent light diffused by surface microstructures are less affected by lighting variation. Laser Speckle Authentication (LSA) [3] leverages the randomness and uniqueness of speckle patterns, enabling robust identification. However, LSA remains highly sensitive to object displacement. Previous studies [4, 5] proposed algorithmic countermeasures, yet few have addressed the design of the optical system from a fundamental perspective, leaving practitioners to rely on trial-and-error setups.



(a) RGB Image

(b) Speckle Image

Figure 1: Speckle images at the back of the playing cards.

This paper presents practical guidelines for designing optical systems suitable for LSA. We theoretically analyze the relationship between speckle size and imaging parameters, and experimentally validate optimal conditions for speckle observation. Furthermore, we explore methods to improve robustness against translational displacement through system design, achieving significant performance gains under real-world conditions.

2 Optics Design for LSA

To ensure clear and reliable speckle images for LSA, this section introduces a design framework for the optical system. We analyze how speckle patterns depend on system parameters like laser spot size, distance to the sensor, and pixel size, and provide practical guidelines for optimal configuration. Unlike previous LSA setups that often include camera lenses and varied illumination angles, our configuration simplifies the optical path and enables a more direct observation of

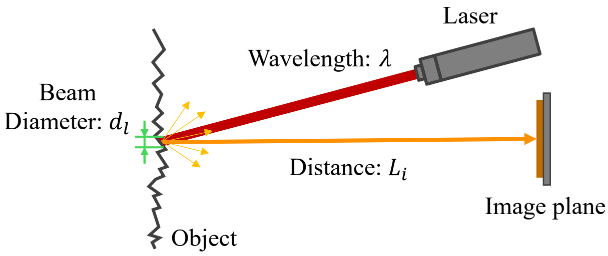


Figure 2: Typical implementation in LSA.

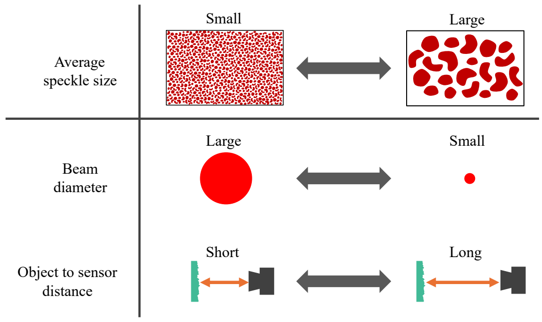


Figure 3: Relationship between speckle size and parameters of optical system.

speckle wavefronts. Figure 1 shows the speckle images obtained when measuring the backs of different playing cards. Although all of the cards have the same print on the back, the captured speckle images show different patterns for each. This is because even for the mass product, the micro-structure of the surface differs and the speckle pattern depends on the fine structure of the object's surface. Previous studies clarified that the minimum size of laser speckles observed in the image plane does not depend on the surface roughness of the object but rather changes with the configuration of the optical system [6, 7]. The following two conditions are assumed for the measurement environment where this condition is satisfied:

1. The diameter of the laser irradiation spot is sufficiently larger than the surface roughness of the measurement object.
2. The surface roughness of the measurement object is larger than one wavelength of the laser light.

These conditions may break down in cases such as mirror surfaces, however they are generally met for typical objects.

Figure 2 shows the typical optics in the LSA. When the laser beam diameter irradiated on the object is defined as d_l, the distance between the object and the image plane as L_i, and the wavelength of the laser light as λ, then the minimum speckle size S_{min} observed in the image plane is expressed by the following equation.

$$S_{\mathrm{min}} = \frac{\lambda L_i}{d_l} \tag{1}$$

The average speckle size S_{avr} is based on the Rayleigh criterion.

$$S_{\mathrm{avr}} = 1.22 S_{\mathrm{min}} \tag{2}$$

Next, we consider the speckle size that can be used as a feature from a pixel size of the image sensor. Based on the sampling theorem, it is considered sufficient if the average speckle size observed by the image sensor is about twice the pixel size. Assuming the pixels of the image sensor are square and denoting the side length of a pixel as L_{px}, the average speckle size that should be satisfied in the constructed optical system is expressed by the following equation.

$$S_{\mathrm{avr}} \geq 2L_{\mathrm{px}} \tag{3}$$

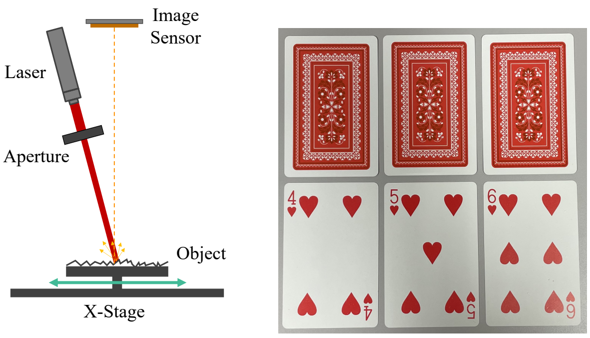
Additionally, increasing the distance between the object and the image sensor leads to larger observed speckle sizes. However, when the average speckle size exceeds the sensor size L_{Sens}, proper observation becomes difficult. Therefore, the distance must be limited so that the average speckle size remains within a valid range. Given the pixel size and sensor size, the average speckle size should satisfy the following condition:

$$2L_{\mathrm{px}} \leq S_{\mathrm{avr}} < L_{\mathrm{Sens}} \tag{4}$$

By configuring the optical system to satisfy the conditions of Eq. (4), it is possible to observe a speckle pattern with optimal visibility for authentication, without causing aliasing. Figure 3 shows the relationship between various parameters of the optical system and the observed speckle size. Increasing the laser beam diameter irradiated on the object can improve robustness against translation, however this results in smaller speckle sizes. In practice, since the complexity of the speckle pattern determines the upper limit of the number of objects that can be authenticated, the distance between the object and the image sensor should be reduced to decrease the average speckle size.

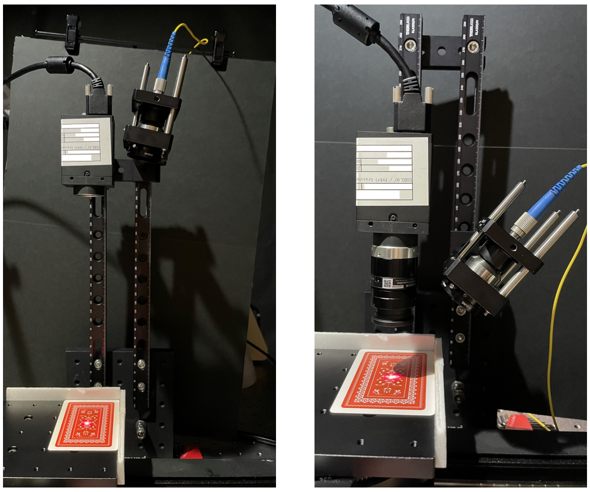
3 Experiment and Discussion

For the configuration of the optical system, an aperture was added to the laser light source shown in Fig. 4 (a) to control the beam diameter, and a translation stage was installed to move the object in parallel. A semiconductor laser with a wavelength of 670.4 nm was used, and the camera was a FLIR GS3-U3-28S5M-C with a pixel size of 4.54 µm square and a resolution of 1920×1440 pixels. Additionally, the back of plastic playing cards were used as the measurement objects. The configuration of the optical system and the measurement objects are shown in Fig. 4. In this experiment, we cropped the input image to 1024×1024 pixels



(a) Optics setup (b) Measurement object

Figure 4: Experiment environment.



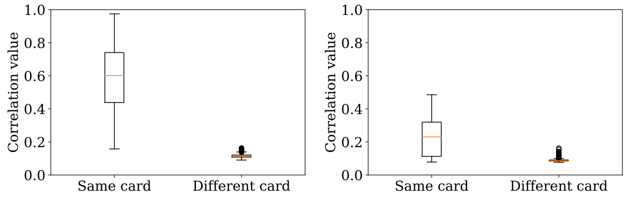
(a) Optimal system (b) Non-optimal system

Figure 5: Configuration of the optical system in Experiment 1.

from the center of the image sensor. We also cropped the template image to 256×256 pixels from the image center of the input and registered in the database. We evaluated object similarity by computing the normalized cross-correlation between the template image and the input image, identifying the pixel with the highest correlation value.

Experiment 1 We constructed two optical systems, one meets the optimal conditions for speckle observation, and the other does not. We evaluated the distribution of correlation values of speckle images between the same and different cards in each system. In the experiment, to meet the optimal conditions as shown in Fig. 4(a), the camera was set at a height of 207 mm from the stage plane using a C-mount lens mount, a collimated laser beam was slightly tilted and irradiated onto the object surface.

As for the optical system configuration that does not



(a) Optimal system (b) Non-optimal system

Figure 6: Correlation value distribution of speckle image groups for each optical system.

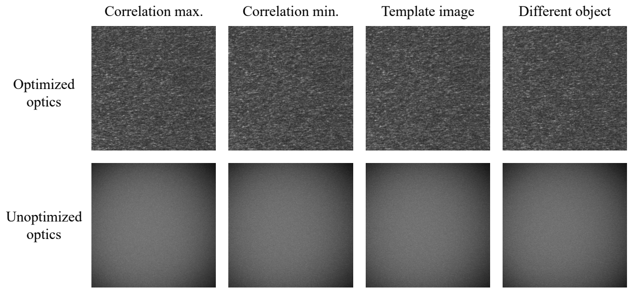
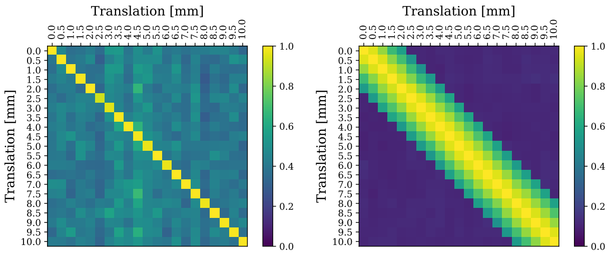


Figure 7: Speckle and template images with maximum and minimum correlation values for each optical system, speckle images observed with different cards.

meet the conditions, refers to the conventional configuration [8], a camera equipped with a 35 mm focal length lens (FUJIFILM HF35XA-5M) was set at a height of 82 mm, F-number was adjusted to 1.9, and the laser light was irradiated onto the object at a 45-degree angle from the optical axis of the camera. The beam diameter emitted from the laser light source was the same in each environment. Figure 5 shows the optical systems used under each condition.

As measurement objects, we use multiple playing cards that have different prints on the front however the same print on the back, as shown in Fig. 5(b). Although the backs are identical in appearance, manufacturing method, and material, the speckle images differ for each individual card. Ideally, an object can be uniquely identified by matching the speckle pattern observed by the camera with a pre-registered pattern.

In this experiment, the backside of 13 playing cards was photographed 9 times in each optical system. To evaluate the potential for accurate individual identification based on image similarity metrics, we examined the distributions of correlation coefficients computed between image pairs of the same card and those of different cards. A complete separation between these distributions would indicate that reliable identification can be achieved through straightforward approaches such as threshold-based classification. In contrast, significant overlap between the two distributions complicates the discrimination task, thereby reducing the overall identification performance.



(a) Beam diameter: 1 mm (b) Beam diameter: 10 mm

Figure 8: Correlation values between speckle images when an object is moved in translation.

Figure 6 shows the distribution of correlation values for the speckle image groups obtained with each optical system. The experimental results indicate that, in the optical system meeting the optimal conditions, the distribution of correlation values between images of the same card and images of different cards is significantly different, allowing for their separation through simple threshold processing. In other words, in an optical system with optimal conditions, it can be said that speckle images are useful enough as feature quantities for individual identification. In contrast, for the speckle image groups captured using the non-optimal system, the distribution of correlation values between images of the same card and images of different cards overlaps, indicating that they cannot be easily separated. This suggests that the speckle images obtained with the non-optimal optical system do not function sufficiently as feature quantities for individual identification.

Figure 7 presents the speckle images of the same card with the maximum and minimum correlation values with the template image, as well as the speckle images of different cards, observed in each optical system. In an optimal optical system, the speckle image with the maximum correlation value and the template image have almost the same pattern, and even when the correlation value is the smallest, an image similar to the template image is observed. In contrast, when comparing the three images observed on the left of the same card of different cards, it is evident that the speckle patterns differ. However, in the non-optimal optical system, high-frequency noise-like speckle patterns are observed. The speckle patterns formed by the wavefronts entering the imaging plane are smaller than the pixel size, thus not capturing the features of the pattern.

Experiment 2 We evaluated the relationship between the laser beam diameter and the robustness to translational movement of the measurement object. In the experiment, we adjusted the aperture size to use two types of laser beam diameters: 1 mm and 10 mm. These were irradiated onto the backside of the playing cards, which were the measurement objects and moved by 0.5 mm increments up to 10 mm, with speckle images captured at each position. We computed the correlation values for the speckle images at each distance to evaluate the robustness of translational movement. The arrangement of the camera and laser was the same as the optical system configuration that meets the optimal conditions constructed in Experiment 1.

Figure 8 shows the correlation values of speckle images when the object is translated for each laser beam diameter. The experimental results show that when the laser beam diameter is 1 mm, the correlation values drop sharply with a movement of about 0.5 mm at any position. This means that even if it is the same card if the laser irradiation position changes even slightly, it will be identified as a different individual. On the other hand, when the laser beam diameter is 10 mm, it is found that not only the diagonal elements but also the surrounding correlation values are high. It is considered that the object can be identified without error if the displacement is about 4.0 mm from the correlation values. However, from the condition of Eq. (4), if the laser beam diameter is increased to improve the robustness against misalignment, the average speckle size becomes smaller. Therefore, there is a trade-off between speckle observation and the improvement of translational robustness.

4 Conclusion

This paper presents design guidelines for laser speckle-based object authentication systems. We analyzed the relationship between speckle size, pixel size, and optical system parameters, and identified the condition summarized in Eq. (4): the average speckle size should be larger than the pixel size however, smaller than the sensor size. Configuring the optical system to meet this criterion allows for the observation of speckle patterns with optimal visibility for authentication, while avoiding aliasing. We experimentally verified that systems meeting this condition produce speckle patterns suitable for individual identification.

Furthermore, we demonstrated that expanding the laser beam diameter to 10 mm significantly improves robustness against translational displacement, achieving a tolerance of approximately 4.0 mm representing an improvement over previous works.

These results suggest that careful optical design can greatly reduce sensitivity to positional misalignment, enabling simpler, more robust authentication systems. The proposed guidelines can help eliminate the need for ad hoc trial-and-error system construction, promoting broader adoption of LSA in practical applications.

Future work includes extending robustness evaluation to optical-axis displacements and angular variations, as well as adapting the system for non-circular illumination patterns.

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