Reference Data Augmentation with Phase Retrieval against Axial Misalignment for Laser Speckle Authentication

Jumpei Naka, Kazuya Kitano, Rui Ishiyama,
Takuya Funatomi, Yasuhiro Mukaigawa
Nara Institute of Science and Technology, 8916-5 Takayama, Ikoma, Nara 6300192, Japan
naka.jumpei.ni8@is.naist.jp

Abstract: This study proposes a method to enhance the robustness of laser speckle authentication against axial misalignment by using speckle patterns captured at different distances and augmenting the reference data through phase retrieval, mitigating accuracy degradation.

1. Introduction

There is a method called artifact metrics that utilizes physical characteristics such as material properties and surface roughness for object identification. This method is expected to be applied in fields such as counterfeit detection and product traceability, as it is difficult to tamper with or replicate. One such technique is laser speckle authentication, which identifies objects based on speckle patterns observed when laser light is irradiated onto the surface of objects with rough surfaces [1]. Since this method utilizes the surface roughness of objects, it allows for highly accurate identification. However, a challenge lies in improving its robustness against misalignment, as the speckle pattern changes significantly when the object's distance shifts.

In this study, we focus on misalignment in the optical axis direction, which connects the object and the imaging sensor. According to Gatti et al. [2], when the distance between the object and the image sensor is fixed, the larger the laser beam diameter, the more significant the changes in the speckle pattern become. In laser speckle authentication, speckle patterns observed at a specific distance are recorded as reference data. Even slight misalignment during observation causes the recorded data to no longer match. Therefore, the larger the laser beam diameter, the worse the robustness against axial displacement becomes.

Previous studies have investigated acceptable tolerances for translational and rotational misalignment [3], but no research has focused on laser speckle authentication addressing distance misalignment and its improvement. Therefore, we propose a method to improve the robustness against distance misalignment by augmenting a small number of reference data. Our approach involves capturing multiple speckle patterns at different distances and densely interpolating and extrapolating the reference data through phase retrieval. This method improves robustness against axial misalignment, regardless of the laser spot diameter.

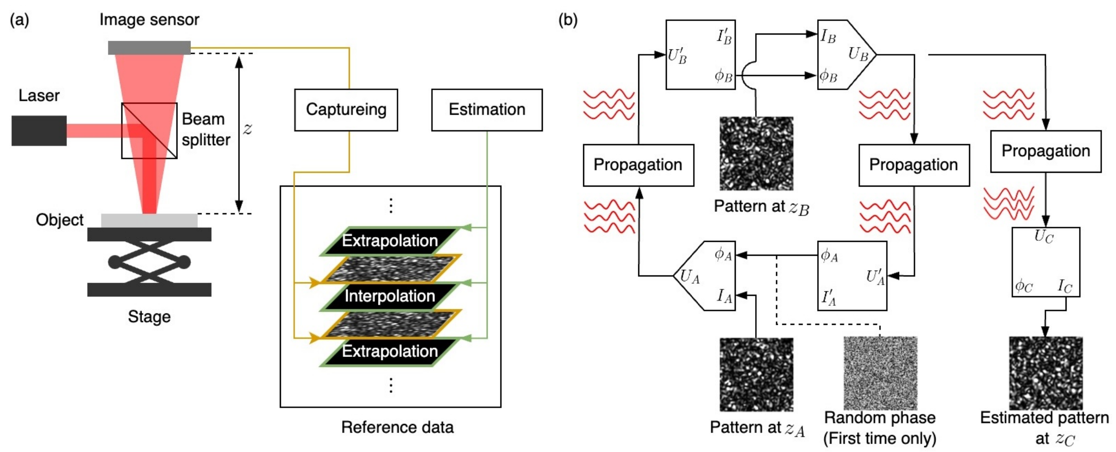

Fig. 1. (a) Schematic of the optical system for speckle imaging and interpolation/extrapolation of reference data. (b) Estimation of speckle patterns using phase retrieval.

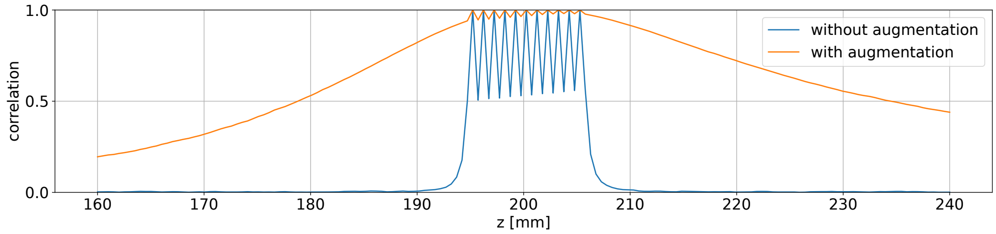

Fig. 2. Simulation result: With or without augmented reference data.

2. Methodology

The procedure for laser speckle authentication is divided into two stages: registration and identification. For the registration, the speckle pattern of the object is recorded as reference data. For the identification, the speckle pattern of the object is compared to the reference data using normalized cross-correlation to search for the matching object. If there is a positional misalignment during registration and identification, the speckle patterns will change, causing the patterns from the same object to no longer match. Taking multiple speckle patterns while moving the object can alleviate the misalignment problem, but the number of images increases. In this study, we augment the reference data through computational processing based on a limited number of speckle patterns.

In the optical system shown in Fig. 1 (a), a laser beam is perpendicularly irradiated onto the object surface via a beam splitter. The distance between the imaging sensor and the object surface can be changed. During registration, multiple speckle patterns of a single object are consolidated into one reference data set, and the data is further augmented through interpolation and extrapolation. Figure. 1 (b) illustrates an example of predicting the speckle pattern at a distance z_C from speckle patterns at two distances z_A and z_B. The prediction involves phase retrieval and propagation calculations using the angular spectrum method. First, the wavefront U_A is constructed from the intensity I_A of the speckle pattern at distance z_A with a random phase. Next, the wavefront U_A is propagated, and the wavefront U_B' at distance z_B is predicted. Then, the wavefront U_B is constructed using the intensity I_B of the speckle pattern at distance z_B and the phase ϕ_B of U_B'. Further propagation is performed on U_B to predict the wavefront U_A' at distance z_A. From the phase ϕ_A and intensity I_A, the wavefront U_A is reconstructed. By repeating this process, the phases ϕ_A and ϕ_B converge. Finally, the wavefront U_B is propagated to predict the wavefront U_C at distance z_C. The intensity I_C of wavefront U_C represents the predicted speckle pattern. By predicting speckle patterns at multiple distances, a series of speckle images can be obtained. Object identification is then performed by calculating the normalized cross-correlation between these generated images and the recorded image.

This method enables the prediction of speckle patterns that account for a wide range of positional misalignment, using only a limited number of speckle patterns. The advantage of this approach is its ability to reduce the number of required image captures while mitigating the effects of positional misalignment during object identification, with a particular effectiveness in addressing axial misalignment.

3. Experimental Result

Through simulation experiments, we evaluated the improvement in authentication accuracy by capturing a small number of speckle patterns within a narrow range along the optical axis and augmenting the reference data. The laser beam diameter was set to 10mm. We assumed that misalignment would occur over a range of 80mm, from $z = 160$mm to 240mm. We created two types of reference data. One consists of 11 patterns taken at 1mm intervals over a 10mm range from $z = 195$mm to $z = 205$mm without augmentation. The other consists of 11 patterns plus interpolation and extrapolation to cover the range from $z = 160$mm to $z = 240$mm with augmentation. In the experiment, we compared the effects of misalignment on identification accuracy between the two reference data.

We computed the correlation between the speckle pattern at a given distance and the reference data for finding the best-matching pattern as the authentication result. As shown in Fig. 2, without augmentation, the correlation values sharply decreased as the distance deviated from the 10mm range used in the registration process. Even within the 10mm range, a drop in correlation values was observed at the gaps between captured patterns. In contrast, with augmentation, the correlation values decreased more gradually, even beyond the 10mm range. Additionally, the correlation values showed minimal decrease at the gaps within the 10mm range. These results demonstrate that augmenting the reference data increases robustness against misalignment during the registration process. Future challenges include conducting experiments in real-world environments, determining the optimal distance intervals for the reference data, and improving the efficiency of the propagation calculations.

References

1. J. D. R. Buchanan, R. P. Cowburn, A. Jausovec, D. Petit, P. Seem, G. Xiong, D. Atkinson, K. Fenton, D. A. Allwood and M. T. Bryan, “Forgery: ‘fingerprinting’ documents and packaging,” *Nature*, 436, 475, 2005.
2. A. Gatti, D. Magatti and F. Ferri, “Three-dimensional coherence of light speckles: Theory,” *Phys. Rev*, A 78(6), 063806, 2008.
3. W. Samsul, H. P. Uranus and M. D. Birowosuto, “Static laser surface authentication with low-cost microscope: Tolerances on spatial and angular disturbance,” *J Opt*, 44, 225–232, 2015.