Precision Measurement Using Template Matching for Laser Speckle Patterns

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Abstract - The accuracy of precision measurement is an essential requirement for precision positioning. This paper presents a new precision measurement method by combining the uniqueness analysis of laser speckle patterns (LSPs) and the template matching algorithm. In this paper, an invariant speckle capturing device and template matching criteria are developed. Experimental results have shown that LSPs can demonstrate different unique and invariant properties even though they are captured from the same material but different samples. Also, accurate direction and displacement information of moving LSPs can be obtained in real-time. Therefore, this merit can provide the potential of speckle pattern analysis for applications of precision positioning in the future.

Keywords – Precision Measurement, Laser Speckle Patterns, Template Matching.

I. INTRODUCTION

Detailed light speckles can be generated by laser light sources via the optical interference reaction [1] and speckle patterns are normally considered as noises that are believed to deteriorate the image quality [2, 3]. While optical speckles are discovered to have relation with the movement, it has been used as sensing techniques for surface displacement, distortion, strain, vibration, rotation and deformation [4,5,6,7].

Compared with the Light Emitting Diodes (LEDs), laser is a light source with high coherence that can directly reflect the surface details suitable for recognition without the need of shadow [8] and the images generated by laser light can provide better resolution quality.

LSPs resulting from field interference contain the 3-D information of illuminated surface and tend to distribute irregularly in tiny spots. Since laser speckle is sensitive to surface profile, speckle patterns are easy to be shaped due to the change of optical phase difference after relative motion such as displacement. It is essential to keep the speckle patterns invariant and reduce the variation of optical phase relative difference for image recognition. The key factors for correctly recognizing LSPs include the adequacy of speckle size [9], the visibility of speckle patterns and, most of all, the speckle invariance in a speckle pattern image. To solve the problems described above, a speckle capturing device is developed first.

Starting from the precision machines, MEMS (Micro Electro-Mechanic System), and going through the current industries such as electric industry, IC manufacturing, IC fabrications and tests, there exist strong demands for precise fixed-position systems and precision metrology in the continuously flourishing development of Hi-technology industry.

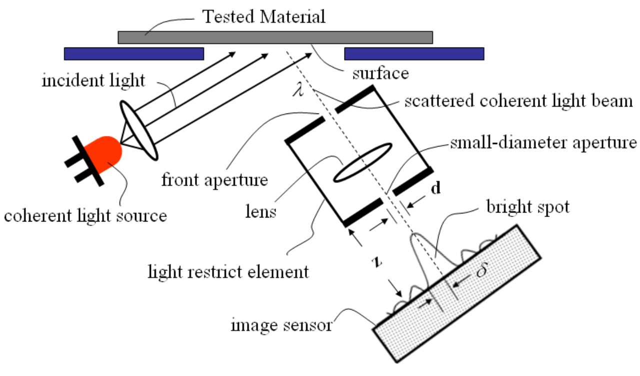

Fig.1 The configuration of the proposed device

This paper presents a new precision measurement method by combining the uniqueness analysis of LSPs and the template matching algorithm. An invariant speckle capturing device and template matching criteria are developed. The proposed configuration is shown in Fig. 1, in which the optical speckle capturing device [10], as shown in Fig. 2, developed by Laser Physics Section of CSIST is adopted. Using the prototype of the optical speckle capturing device, LSPs captured from the test material is demonstrated to be invariant. Due to the invariance and feature richness of captured speckle patterns, they can be considered and used for object identification. On the other hand, since the 3D texture of the object surface is very hard to be deliberately replicated, this is also a merit for authority protection. For object identification, the speckle patterns captured from an object surface are matched with those patterns in the database and then an object can be identified and discriminated. Since accurate direction and displacement information of moving speckle patterns can be obtained in real-time, this can be further used for precision positioning.

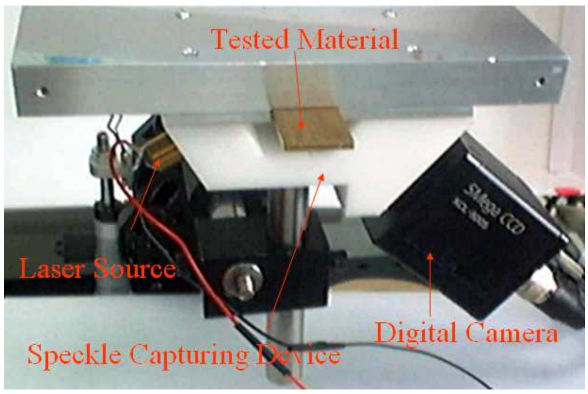

Fig. 2 The proposed device

This paper is organized as follows. Section 2 introduces the principles of laser speckles. Also, the proposed methods for building a speckle identification system are described. Experimental results are illustrated and discussed in Section 3 to demonstrate the possibility of applying at precision positioning in the future, prior to Conclusions in Section 4.

II. PRINCIPLES OF LASE SPECKLES

As shown in Fig. 1, a highly coherent light is emitted from a laser light source and then the scattered lights from the surface pass through a light restrictive element. The light restrictive element is implemented with an aperture and lens, resulting in the diffractive effect for the incoming scattered lights. Then the diffractive effect forms several concentric rings called Airy disks on the image sensor. The half-width δ of the central bright spot, the wavelength λ of light wave, the diameter d of the aperture, and the distance z between the aperture and the image sensor satisfy the following relation:

$$\delta = 1.22\frac{\lambda}{d}z \quad . \tag{1}$$

Given the wavelength λ of the laser light source, the size of bright spot can be adjusted through the ratio of z/d. The spot size should be larger than the minimum cell size of image sensor for the image to be recognized. In general, the δ value is designed to be close to the cell size of image sensor. Therefore, the image sensor can detect miniature bright spots and the resolution is increased in this way.

Each of the scattered light from adjacent scattering points of the illuminated surface passes through the light restrictive element. Therefore, different bright spots interfere with each other resulting in a distribution of bright and dark spots that forms a speckle pattern. If the lights come from a scattering point and its adjacent scattering points generate constructive interferences on the image sensor, then a bright and large size speckle will be created. As shown in Fig. 1, a convergent lens and a front aperture are introduced along the optical path to confine the incident angle of the scattered light from the surface, i.e. to restrict the image captured area on the surface. Once the image captured area is limited, the maximum variation of optical path difference $\lambda/5$ can be satisfied and a shape-invariant speckle image is obtained from the image sensor while a relative motion occurs between the optical speckle capturing device and the surface [11].

By properly adjusting the diameter and the position of the aperture, the speckle size can be enlarged and the capturing area from the surface can be limited. Then the resulted speckle can be shifted accordingly and the speckle pattern is invariant with respect to the relative motion.

III. EXPERIMENTAL METHODS

As shown in Fig. 3, an experimental speckle capturing system is built for analysing the speckle patterns. The system consists of the speckle capturing device, the personal computer with an image frame grabber, and the manual moving stage. The speckle capturing device includes the laser diode, the optical lens and off-the-shelf high resolution digital cameras constituting the image sensor. The wavelength of laser light is 650 nm and the pixel size of image sensor is 3.45 μm×3.45 μm. The resolution of image sensor is designed to be 2448×2050, but the area of 64×64 pixels is adopted as the WOI (Window of Interest) and transmitted to the frame grabber. Due to that the magnification of the optical capturing device is designed to be 0.5, the covered image area by the 64×64 pixels is about 442 μm^2 (64×3.45μm×2). The manual moving stage results in a relative movement between the speckle capturing device and tested materials.

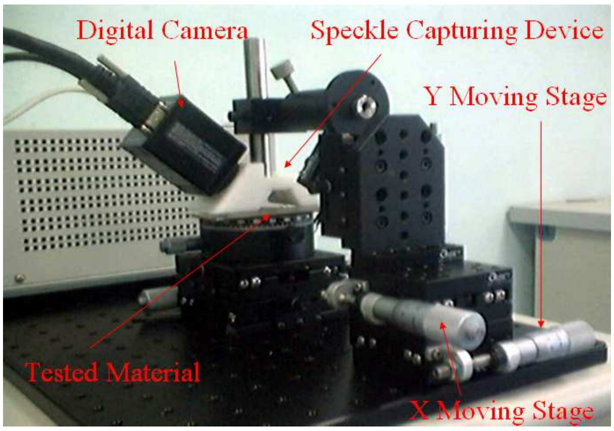

Fig.3 Experimental speckle capturing system

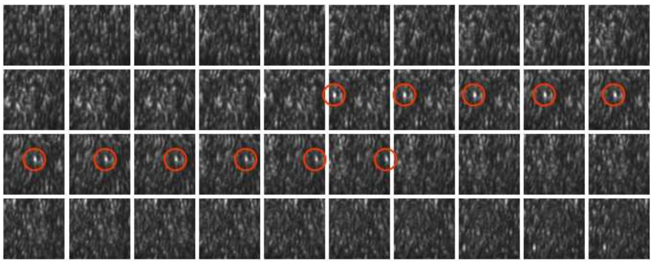

Fig.4 Exemplar speckle patterns of tested material

By moving the stage in one direction with a step size of 50μm, the resulted sample image sequences for the test materials (here is the aluminium pad) moving in the X-direction are shown in Fig. 3.

As demonstrated in Fig. 4, the speckle patterns captured from test materials are shape invariant. Since the image sensor can accurately capture the shape of the speckle during the movement of the sensor relative to an object surface, this invariance property becomes a feasible feature for the applications of precision positioning and recognition.

As shown in Fig. 5, using the approach of template matching under different template sizes, the analysed relationship between the correlation coefficient and the displacement is displayed. While the moving range of speckle pattern is between ±500μm, this means the displaced speckle is still partly overlapped with the original speckle. However, there is no overlapped area after the moving range of speckle pattern is over ±500μm.

Experimental results reveal that when the template size is small (e.g. 10 μm), the average value difference between the main lobe (C_{avg_main}) and the side lobe (C_{avg_side}) is not much. The ratio value of $C_{avg\_main}/C_{avg\_side}$ is greater than and close to one. When the template size is gradually increased, the ratio value of $C_{avg\_main}/C_{avg\_side}$ is much greater than one. The larger this ratio value becomes, the easier the correlation coefficient is used as the threshold to estimate the correlation and similarity between the original speckle pattern and the displaced pattern image.

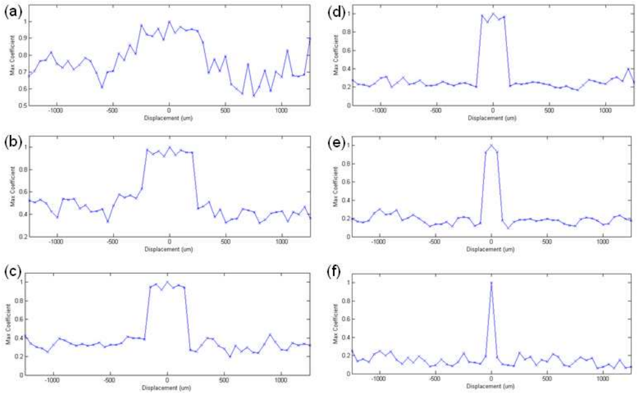

Fig.5 Template Size (a) 10×10 (b) 20×20 (c) 30×30 (d) 40×40 (e) 50×50 (f) 60×60 pixels

On the other hand, we have also found that when the template size is small (e.g. 10μm), the width of main lobe in the overlapped area (±500μm) is wider and close to the width of overlapped area. The width of main lobe is gradually reduced while the template size is increased. This means that using the same coefficient threshold, the displacement range of highly-correlated speckle images is affected and reduced. Take Fig. 5(b) as an example and set the template size to 20μm. The displaced LSPs can be considered as highly correlated while the coefficient threshold value is set to 0.8 and the displacement range is under the range of ±200μm. When the the template size is set to 50 μm, as shown in Fig. 5(e), the range of highly correlated area is reduced to ±50μm. This trend can be found by referring to Fig. 6. Therefore, while template matching is used to recognize overlapped object surfaces, due to the characteristic of uniqueness, the accuracy becomes higher while the template size is large (e.g. 60×60). This can be used for precise measurment. However, the characteristic of uniqueness diminishes while the template size is small (e.g. 20×20) and the displacement error is allowed.

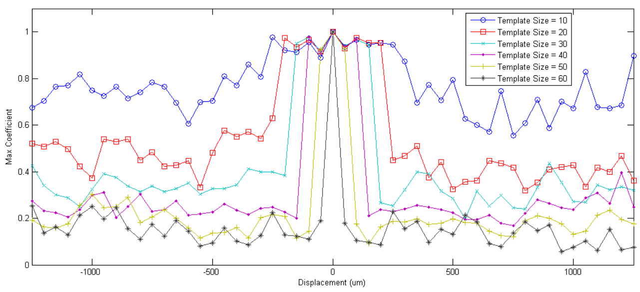

Fig.6 Coefficient vs. Displacement in different template sizes

By conducting new experiments under the same configuration, each speckle image is captured after the stage is moved at the step size of 500μm. Since speckle images are non-overlapped to each other, each image can be simulated as a totally different object card with its own unique surface. Figure 7 displays 40 image examples of speckle patterns showing the uniqueness of speckle textures. As shown in Fig. 8, the 21-th object card is adopted and used to do template matching individually with those object cards from the first to 41-th object card. Experimental results show that the highest correlation coefficient is only obtained while the template matching is done by matching the 21-th object card to its own card. The correlation coefficient becomes low while the 21-th object card is matched with the other cards, this effect turns especially apparent while the template size becomes larger (e.g. 60×60). By observing from the experimental results, LSPs can provide the characteristic of uniqueness, this exists even different object surfaces of same material are used. This comes from that the object surface texture can not be duplicated and LSPs are captured from those reflected textures of object surfaces. Since LSPs have the feature of uniqueness, this merit is feasible for object surface recognition and precision measurement or positioning.

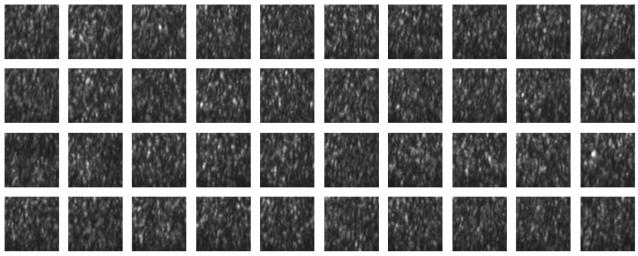

Fig.7 Forty non-overlapped image examples of LSPs from different areas

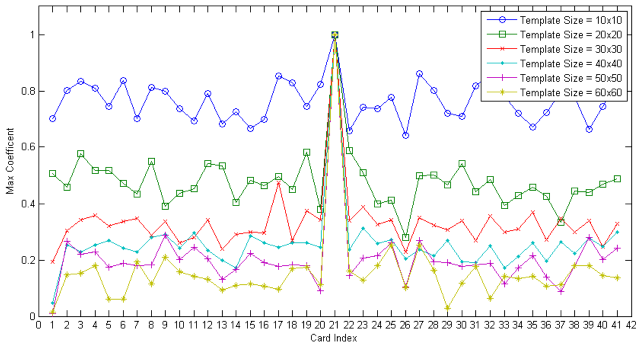

Fig. 8 Coefficient vs. Different Card in different Template Size

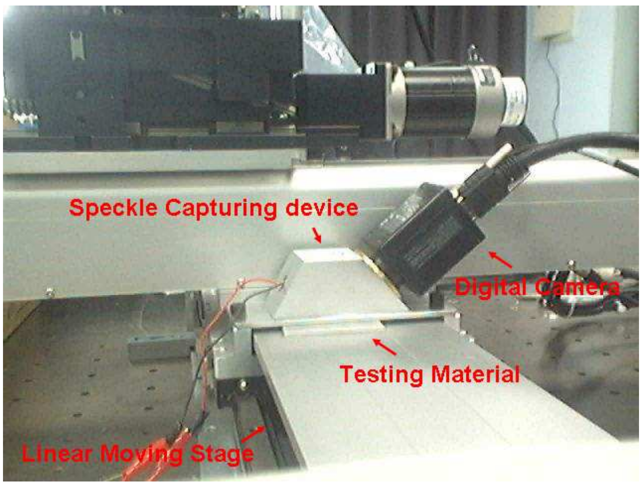

Fig.9 The configuration of image capturing device for LSPs

To further evaluate the detection accuracy using LSPs and NCC (Normalized Cross Correlation) template matching, we have designed the test configuration as shown in Fig. 9. The LSP capturing device is mounted on top of the linear moving stage and used to capture the object surface image on the bottom of the device. By controlling the movement of linear moving stage, the LSP of object surface can be captured in real time and transmitted to the personal computer in which the NCC template matching can be performed.

Fig. 10 shows the developed Graphical User Interface (GUI) program under Windows operating system. This GUI program can be used to easily control the movement of the linear moving stage, display the LSPs in real time, and calculate the displacement distance between two images using the method of NCC Template matching.

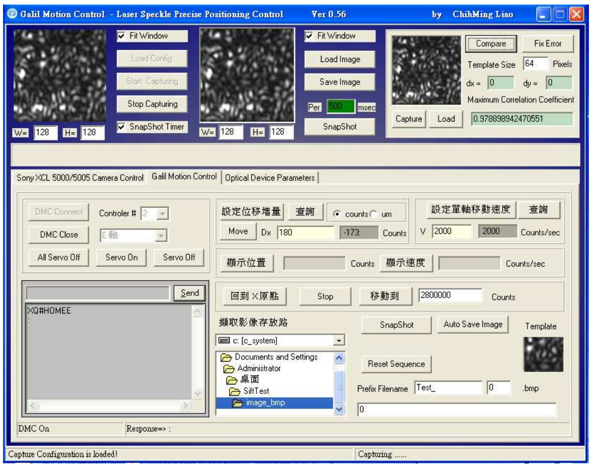

Fig.10 Servo motor control and image analysis GUI program

Fig.11 shows experimental results by moving the linear moving stage in a step size of 1μm and the total accumulated distance is 40μm. The LSPs are captured after each movement. Each image in the sequence of captured LSPs is matched with the LSP of the origin in order using NCC template matching. The individual relationships of NCC ratio and CCD pixel distance to the platform moving distance are drawn in Fig. 11. The red line indicates the changes of NCC curve after each movement and the blue line reveals the results of detected pixel moving distance after template matching.

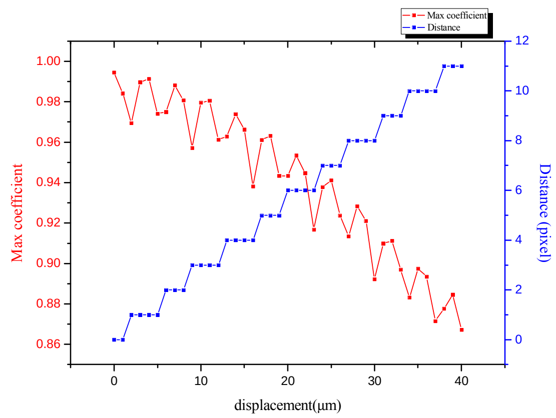

Fig.11 Actual distance (μm) vs. normalized cross correlation (NCC) (%) and calculated moving distance (pixel)

Due to that the magnification of the optical capturing device is designed to be 1, and the CCD pixel size of the LSP captured device is 3.45μm×3.45μm, according the blue line, after 3 to 4 movements, a pixel distance of 3.45μm is obtained after NCC Template matching. Therefore, we can conclude that by integrating the invariant LSP capturing device and the method of NCC Template matching, the relative displacement of object surface can be detected and the accuracy can reach to a pixel size (3.45μm in this paper). This advantage can be deployed for applications of precision measurement, precision alignment, or precision positioning.

IV. CONCLUSIONS

In this paper, we have successfully demonstrated that by integrating the invariant LSP capturing device and the method of NCC Template matching, the relative displacement of object surface can be detected and the accuracy can reach to a pixel size. Therefore, template matching is suitable for the matching of invariant speckle images by setting adequate coefficient threshold values. This advantage can be deployed for applications of precision measurement, precision alignment, or precision positioning. On the other hand, due to that the LSP is generated from the 3D object surface and its natural texture is hard to be duplicated, this can be used for personal identification or object recognition in the future.

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