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Improving fringe projection efficiency using region-based phase unwrapping in the spatial domain

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Abstract

In fringe projection systems, three-dimensional (3D) information is primarily extracted from phase data. During the prior phase demodulation step, phases are wrapped between $-\pi$ and π due to the range bound of the arctangent function. Although various phase unwrapping methods exist, efforts continue to focus on reducing errors and improving the speed of phase unwrapping. This study introduces a novel region-based phase unwrapping method designed to enhance both accuracy and performance speed. The proposed method uses only a reference high-frequency wrapped phase map of a reference plane, obtained during system calibration, to unwrap the target wrapped phase of the object to be measured. A Laplace filter, followed by binarisation, is applied to the reference wrapped phase maps to localize regions bounded by phase jumps. The presence of objects shifts certain region boundaries in the target phase map, resulting in matched and mismatched regions. Matched regions inherit indexes from the reference map, while mismatched regions are segmented and indexed based on neighbouring indexes and the projector-camera orientation. After labelling, each region's index is multiplied by 2π and added to the target wrapped phase map, yielding the relative unwrapped phases. Absolute phases are then determined by projecting a sample point onto the reference plane, calculating its actual phase, and comparing it to the corresponding point in the relative unwrapped phase map. The phase difference is then used to adjust the entire relative unwrapped phase map. Simulation and experimental results show that the proposed method significantly improves time efficiency. Additionally, the method minimizes errors through the integration of a background removal technique in the developed algorithm. This approach is particularly suitable for cases where the measured object's depth corresponds to a phase range within 2π, making it especially applicable to surface measurement such as in-situ layer measurements in additive manufacturing.

Keywords: Phase unwrapping, Laplace filter, Binarization, Labelling, Fringe projection, Phase demodulation

1. Introduction

Due to its typical features of being non-contact, accurate, high-resolution, fast, and capable of full-field measurement, Fringe Projection (FP) profilometry has been widely applied in various fields, including biomedicine, virtual reality, engineering, chemical industries, and other industrial applications for three-dimensional (3D) measurements [1–7]. A basic FP system consists of a camera, a projector, and a processing unit (computer). Under the control of the processing unit, a series of digital fringe patterns are projected onto the target object. The camera captures the resulting deformed fringe patterns, which contain phase information about the projected patterns [8]. The assigned algorithm extracts the phase information from the deformed fringe patterns and converts the extracted phase to real-world 3D coordinates of the object. In order to measure the surface or form of an object using phase information, a number of FP techniques have been proposed, among which phase-shifting and Fourier transform are two frequently used fringe analysis algorithms [2, 3], yet these methods can only estimate the phase distribution by performing an arctangent calculation, resulting in the wrapped phase ranging from $-\pi$ to π. Therefore, it is essential to implement phase unwrapping after phase demodulation process. There are various techniques used to eliminate this phase ambiguity. The conventional spatial and temporal phase unwrapping methods have been practiced widely to date [3, 7, 9].

The spatial phase unwrapping (SPU) method detects and removes the 2π phase jumps based on the phase difference between adjacent pixels, while the temporal phase unwrapping (TPU) method eliminates phase ambiguity by projecting additional patterns to uniquely label each period of the wrapped phase. SPU methods can achieve rapid measurement because few fringe patterns are required to be projected but are not suitable for measuring objects with large gradients and discontinuous profiles due to the dependency on adjacent pixels for phase unwrapping [2, 10]. In addition, SPU methods are susceptible to noise, these methods are easy to introduce the phase errors in the process of phase retrieval, and these errors propagate to adjacent pixels during the unwrapping process. Unlike SPU, TPU methods have been proposed to achieve pixel-by-pixel, which makes a robust absolute phase unwrapping by projecting additional pattern.

To improve the speed of 3D measurements, many authors have proposed different measurement techniques, particularly utilising SPU methods, as referenced in [11] . However, errors in the unwrapping path propagate and accumulate in all consecutive pixels, making the results less reliable.

Even though the above traditional methods are commonly used in practice, various research efforts have been undertaken to address the trade-off between enhancing accuracy and improving performance speed. Among these, various machine learning models have gained significant attention [2, 7, 9]. Similarly, optimizing traditional methods is also considered a viable option for enhancing the performance of FP systems [12]. Considering the advantages of the SPU method, which achieves phase continuity without requiring additional patterns, it becomes particularly relevant for specialized applications like additive manufacturing, where phase ambiguity is minimized due to target object height differences.

In this study, we aim to address the trade-off between improving both accuracy and performance speed. This paper proposes a novel regional based phase unwrapping method in the spatial domain to enhance both accuracy and performance speed. The proposed method uses only a reference high-frequency wrapped phase map of the reference plane, obtained during the system's characterisation, to unwrap the target wrapped phase of the object to be measured. An image processing algorithm is applied to both the reference and target wrapped phase maps to localise regions bounded by phase jumps. The presence of objects shifts certain region boundaries in the target phase map, resulting in matched and mismatched regions. Region labelling is then performed based on these shifts. Simulation and experimental results demonstrate that the proposed method significantly improves time efficiency. Additionally, the method minimises errors by integrating a background removal technique into the proposed algorithm.

2. Principle

2.1. Basic principle of finge projection

In FP, the fringe distortion is quantified by its phase distribution, which can be converted to the surface profile of the measured object. Many fringe analysis techniques have been proposed to extract the phase distribution from distorted fringes. In phase-shifting profilometry (PSP), a series of fringe patterns are projected onto the surface of the target object using a projector [8]. Simultaneously, a camera captures both the reference fringe pattern and the deformed fringe pattern caused by the surface of the object. The captured fringe patterns are then transferred to processing computer, where the wrapped phase of the captured fringes is computed.

The distribution of distortion fringes captured by the camera can be expressed as:

$$\mathrm{I_n(x,y) = A(x,y) + B(x,y)cos}\left[\phi(\mathrm{x,y}) - \frac{2\pi \mathrm{n}}{\mathrm{N}}\right], \quad (1)$$

where (x, y) are the pixel coordinates, $I_n(x, y)$ is the intensity of the fringe pattern, the sub script n denotes the n-th phase-shifted fringe pattern, N is the number of phase shifts, $A(x, y)$ is the average intensity of sinusoidal fringe, and $B(x, y)$ is the fringe modulation intensity. $\phi(x, y)$ represents the wrapped phase map due to the height of the target object which can be calculated using the least squares method by the following equation:

$$\phi(\mathrm{x,y}) = \arctan\frac{\sum_{\mathrm{n=0}}^{(\mathrm{N-1})} \mathrm{I_n(x,y)}\sin\left(\frac{2\pi \mathrm{n}}{\mathrm{N}}\right)}{\sum_{\mathrm{n=0}}^{(\mathrm{N-1})} \mathrm{I_n(x,y)}\cos\left(\frac{2\pi \mathrm{n}}{\mathrm{N}}\right)}, \quad (2)$$

As discussed previously, the wrapped phase computed from this equation is bounded within the range of $-\pi$ to π. Therefore, phase unwrapping methods are employed to recover the absolute phase for 3D shape reconstruction.

The mathematical relation between the wrapped phase and the absolute phase can be described as:

$$\Phi(\mathrm{x,y}) = \phi(\mathrm{x,y}) + 2\pi \mathrm{K(x,y)}\,, \quad (3)$$

where $\Phi(x, y)$ is the absolute unwrapped phase and $K(x, y)$ is the fringe order. Thus, all the phases unwrapping techniques presented are mainly targeted to determine the fringe order $K(x, y)$ for each pixel in a fast and accurate way [6]. Likewise in this study a regional based phase unwrapping is proposed to determine the phase order in spacial domain.

2.2. The proposed phase unwrapping method

As illustrated in the flowchart in Figure 1, three high-frequency sinusoidal fringes with a $2\pi/3$ phase shift are projected onto the target object and reference plane. Wrapped phases are calculated from the captured images as in Eq. (2) and are subsequently used to convert the phase map data into an image suitable for image processing operations, as shown in Figure 2(a) and 2(b).

A Laplace filter, binarisation, and padding are applied to localise regions bounded by phase jumps on a reference phase maps, thereby generating phase boundaries. Using this regionally bounded reference phase image, the proposed algorithm assigns an incremental index for each connected region from top-left and moving left to right, as shown in Figure 3(b).

The presence of the target object on the wrapped phase map introduces shifts in certain regions. These regions are segmented by subtracting the wrapped phase containing the target object from the reference wrapped phase, as shown in Figure 2(c). The segmented regions are indexed based on neighbouring indices and the projector-camera orientation. Once both phase maps are labelled, they are logically combined to create a single labelled image, as depicted in Figure 3(d). This labelled image is then multiplied by 2π and the wrapped phase map of the target object is added (Figure 3(e)). This results the relative unwrapped phase without considering phase jump edges.

Finally, these edges are filled using inward interpolation from the pixel values along the region boundaries. This step is particularly effective in restricting error propagation, which is a known issue in spatial phase unwrapping. Additional processing is required to transform the relative unwrapped phase map into an absolute phase map.

Absolute phases are then determined by projecting a sample point onto the reference plane, calculating its actual phase, and comparing it to the corresponding point in the relative unwrapped phase map. The phase difference is used to adjust the entire relative unwrapped phase map accordingly.

The segmented wrapped phase maps of the target object are further processed using logical and morphological operations, and all foreground binary images are merged to generate a convex hull image. This image serves as a mask to exclude the background and minimize outliers, as shown in Figures 3(g) and 3(h).

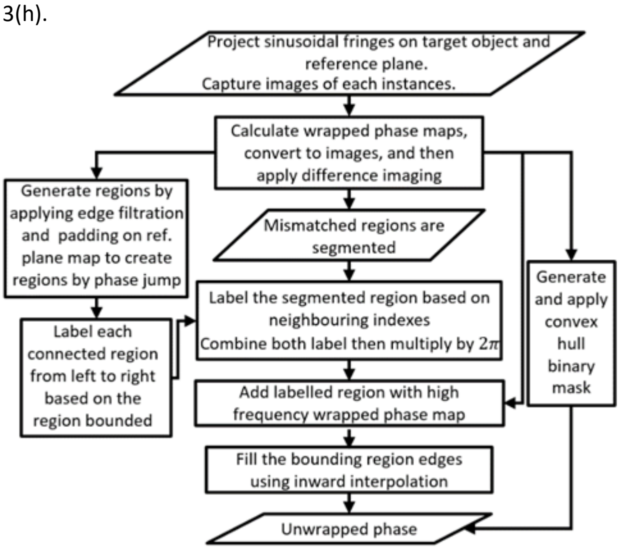

Figure 1. Flow chart of methodology.

Figure 2. Segmentation of mismatched region in comparison with reference phase map (ø100 × 1 mm target).

3. Simulation and experimental setup results

The FP system is simulated in a virtual environment (Blender) to evaluate the performance of the system and its configuration [13]. In Blender FP simulation, a spotlight acts as a projector, projecting a set of prepared digital fringes onto the target object and reference plane. Similarly, a virtual camera with a resolution of 5496 × 3672 pixels and lens with focal length of 17 mm is assigned to sequentially capture each instance of the projected fringes. Once the captured images are rendered and stored in the processing unit, these images are further utilised to calculate the wrapped phases, which are subsequently unwrapped using the proposed method. These fringe analysis and 3D reconstruction calculations are performed in MATLAB.

Figure 3(a) – 3(i) illustrates the relative unwrapped phase obtained using the proposed method. Figures 3(a) and 3(b) illustrate the region boundaries defined and labelled by the proposed method, using the reference phase map as input. As shown in the cross-sectional data of the labelled image in Figure 3(c), the edges used to define the regions were initially excluded. This exclusion was intentional to prevent error propagation across the boundaries, a common issue in spatial phase unwrapping.

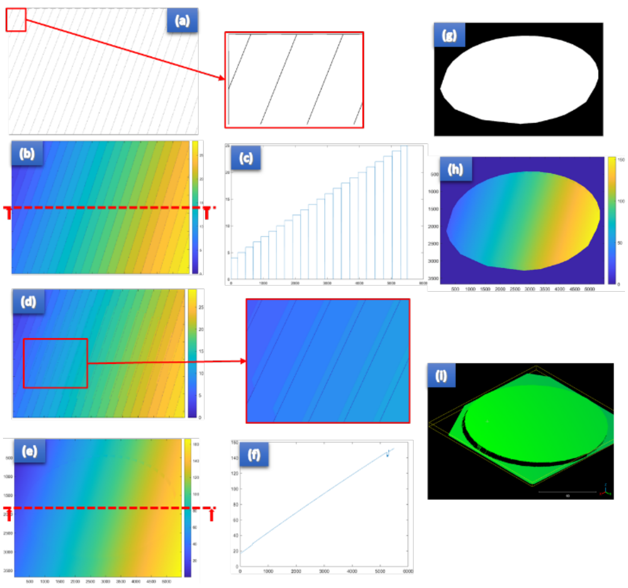

Figure 3. The proposed phase unwrapping method (ø100 × 1 mm target).

Once the unwrapping is completed, these edges are filled using interpolation, considering both edges of consecutive regions. Figure 3(d) depicts the phase order indexed by the proposed method, while Figures 3(e) and 3(f) present the relative unwrapped phase, generated by multiplying 2π and combining it with the high-frequency unwrapped phase of the target object. Subsequently, as mentioned in Section 2.2, absolute phase analysis and background removal are performed sequentially, followed by 3D reconstruction.

To evaluate the performance of the proposed method, a commonly implemented counterpart, the multi-frequency (hierarchical) temporal phase unwrapping method with three phase shifts was also simulated using the same hardware features.

As shown in Figure 4, a spur gear with outer diameter 50 × 1 mm is used as the target object in the Blender environment. A sequence of fringe patterns is projected onto the surface of the target, and a virtual camera sequentially captures each instance. The rendered images are stored on a processing computer. Phase demodulation is followed by phase unwrapping, performed using both the proposed method and the hierarchical temporal phase unwrapping method. The 3D reconstruction results from both methods are evaluated in CloudCompare software using the multiscale model-to-model cloud comparison (M3C2).

The 3D reconstruction results from both methods demonstrate perfect alignment with minimal outliers, indicating that the proposed method performs comparably to the hierarchical method. This outcome is achieved using a single reference wrapped phase map taken during calibration. Thus, the mask generated by the proposed method effectively eliminates errors caused by environmental noises, including interference from unwanted light sources.

The proposed method achieves high-speed measurement while extracting more accurate unwrapped phase data. Similarly, as illustrated in Figure 4(a) – 4(d), the reconstructed 3D maps from both methods demonstrate perfect alignment, with an average outlier deviation of only 0.0345 µm in the reconstructed point cloud. This result highlights the potential of the proposed method to address the trade-off between maintaining the accuracy of phase unwrapping and improving the speed performance of the FP system.

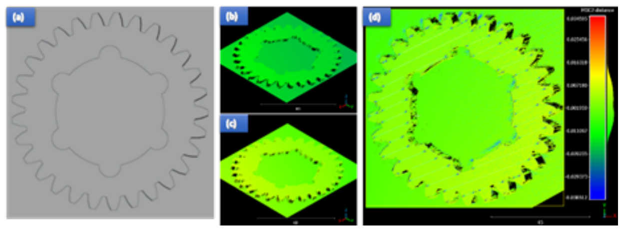

Figure 4. Comparative assessment of the proposed method (b) and the multi-frequency temporal phase unwrapping technique (c) on 3D spur gear reconstruction.

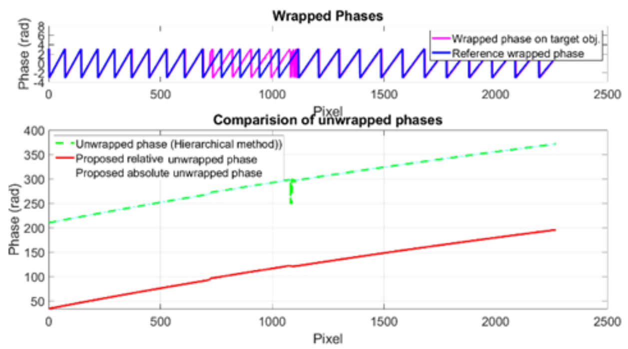

Figure 5. Phase unwrapping comparative results for coin 3D reconstruction taking sample column vector phase data.

Similarly, experimental attempts were conducted to evaluate the accuracy of the proposed method. A DLP LightCrafter 4500 projector, with a resolution of 912 × 1140 pixels, was used to project sequential digital fringes onto the surface of the target object. In this study, a Basler ACA5472-17um monochromatic camera with a resolution of 5472 × 3648 pixels and a 17 mm focal length lens was employed. A coin and a checkerboard were considered as test objects.

Likewise, experimental phase unwrapping was performed using the proposed and hierarchical methods, and the results are presented in Figures 5 and 6. The unwrapped phase demonstrates that the proposed method exhibits significantly reduced noise, with the remaining phase showing near-perfect alignment with the well-established hierarchical method. These findings confirm that the proposed method achieves high-accuracy phase unwrapping using only a single wrapped phase on a reference plane. Moreover, compared to the multi-frequency phase unwrapping method, which requires multiple frequencies and phase-shifted images, the proposed method delivers a substantial improvement in speed performance. The results also clearly demonstrate the effectiveness of the proposed method in mitigating error propagation.

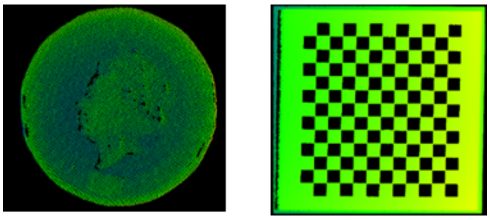

Figure 6. Experimental reconstruction of the 3D shapes of a coin and a checkerboard using the proposed phase unwrapping method.

4. Conclusions

This study introduced a novel regional based spatial phase unwrapping method designed to address the trade-off between accuracy and performance speed in FP systems. The proposed method uses the phase-shifting technique to compute the wrapped phase, with a reference phase map employed to unwrap the high-frequency wrapped phase of the target object. The algorithm converts phase maps into images and applies binarization, edge filtering, and padding to define regions for labelling. Labelling is performed on the reference phase map by sorting connected region from top-left and moving left to right. For mismatched regions in the target phase map, segmentation and indexing are guided by neighbouring regions and the camera-projector orientation. Simulation and experimental analysis compared the method with the multi-frequency phase unwrapping approach. Results demonstrated that the proposed method achieved high accuracy and performance speed without requiring additional frequency images. The algorithm also effectively removed background noise, enhancing measurement accuracy. This approach is particularly suited for scenarios where the object's depth corresponds to a phase range within 2π, making its potential for surface measurement applications, such as in-situ layer measurements in additive manufacturing.

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