Phase recovery from a single fringe pattern using an orientational vector-field-regularized estimator

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Recent studies have demonstrated that the phase recovery from a single fringe pattern with closed fringes can be properly performed if the modulo 2π fringe orientation is estimated. For example, the fringe pattern in quadrature can be efficiently obtained in terms of the orientational phase spatial operator using fast Fourier transformations and a spiral phase spectral operator in the Fourier space. The computation of the modulo 2π fringe orientation, however, is by far the most difficult task in the global process of phase recovery. For this reason we propose the demodulation of fringe patterns with closed fringes through the computation of the modulo 2π fringe orientation using an orientational vector-field-regularized estimator. As we will show, the phase recovery from a single pattern can be performed in an efficient manner using this estimator, provided that it requires one to solve locally in the fringe pattern a simple linear system to optimize a regularized cost function. We present simulated and real experiments applying the proposed methodology.

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1. INTRODUCTION

Fringe pattern analysis has been a widely studied topic owing to its relevance in optical metrology and interferometry for the measurement of physical quantities. In fringe pattern analysis the aim is to recover the phase that modulates a two-dimensional cosine function, and the intention of most proposed algorithms for phase recovery is to find either two functions in quadrature or an analytic function whose argument is the desired phase. In the particular case when there is no single dominant frequency in the pattern, the fringes form closed curves, and a common approach for phase recovery such as the Fourier analysis[1] does not work properly. On the other hand, several experimental methods have been developed that permit the acquisition of several images in order to apply phase-stepping algorithms[2] without the need of a fringe carrier. However, there are some situations in which these methods cannot be applied, for example, in the study of fast transient phenomena. For these reasons it is important to develop methodologies for phase recovery from a single fringe pattern without a carrier.

A single pattern without a carrier, however, has not been easy to deal with. Owing to ambiguities in the fringe pattern formation process, a main drawback analyzing this type of fringe pattern is that several solutions of the phase function satisfy the original observed signal, so it is necessary to restrict in some way the solution space. As in most practical cases, the phase to be recovered is a continuous function, so we propose an algorithm that finds only smooth functions.

Some powerful methodologies for the demodulation of fringe patterns with closed fringes have been reported in past years[3–5] that propose to solve the problem of phase recovery from the regularization point of view. In Refs. 3 and 4 the main research is focused on solving locally at every site in the fringe pattern a nonlinear system for optimizing a regularized cost function that models a small region to be locally monochromatic in order to detect the parameters of a local phase plane. In Ref. 5 the strategy is to retrieve an analytic function through the estimation of local frequencies of the fringe pattern by successive decoupled estimations of the fringe orientation and the magnitude of the local frequency; however, the minimization of several cost functions makes this methodology difficult to implement. Although these regularization techniques are robust for phase recovery, their main inconveniences are the computational complexity and the long processing time.

Recently reported studies[6,7] have evidenced the importance of the fringe orientation angle for the demodulation of fringe patterns with closed fringes. The purpose of the work reported by Servín *et al.*[6] is to estimate the phase by means of the proposed n-dimensional quadrature transform, which involves the fringe pattern gradient and the modulo 2π fringe orientation.

As mentioned above, the traditional Fourier analysis

