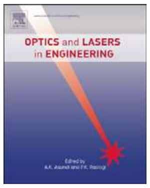
Optics and Lasers in Engineering 48 (2010) 650–656

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



Anisotropic phase-map denoising using a regularized cost-function with complex-valued Markov-random-fields

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ARTICLE INFO

Article history:
Received 29 October 2009
Received in revised form
29 January 2010
Accepted 6 February 2010
Available online 26 February 2010

Keywords:
Regularization
Phase-map filtering

ABSTRACT

In our recently reported work [1] (Villa et al., 2009) we derived a regularized quadratic-cost function, which includes fringe orientation information, for denosing fringe pattern images. In this work we adopt such idea for denoising wrapped phase-maps. We use a regularized cost-function that uses complex-valued Markov random fields (CMRFs) with orientation information of the filtering direction along isophase lines. The advantage of using an anisotropic filter along isophase lines is that phase and noise can be properly separated while 2π phase jumps are preserved even in high frequency zones. Apart from its robustness, the outstanding advantage of our method is its minimal computational effort. We present some results processing simulated and real phase-maps.

1. Introduction

In fringe pattern analysis the aim is to recover the phase that modulates the fringes. The phase is important because it is continuously related with a physical quantity, such as wave fronts, topography, etc. However, most fringe demodulation techniques give the phase wrapped, so that the continuous phase must be obtained by means of the well-known unwrapping process. Phase unwrapping is an important and well-known task in several areas [2], such as speckle interferometry [3], holographic inteferometry [4], profilometry [5] and remote sensing [6,7].

To briefly describe the unwrapping problem we define the continuous phase field as ϕ_r, where $r=(i,j)$ is the vector of image coordinates in a regular lattice L. The wrapped phase (i.e. the observed phase) is then defined as $\alpha_r = W[\phi_r]$, where W is the wrapping operator such that $\alpha_r \in [-\pi, \pi)$.

The problem of recovering the continuous phase ϕ_r from α_r may be solved if we have prior information about ϕ_r. For example if we know that ϕ_r varies slowly from pixel to pixel, the relation

$$W[\nabla\alpha_r] = \nabla\phi_r \tag{1}$$

holds. In other words, the wrapped gradient of the wrapped phase equals the gradient of the continuous phase. Consequently, the recovery of the continuous phase without ambiguities is possible by summation of the wrapped gradient of α_r. Unfortunately, in many practical situations the observed phase α_r is affected by noise, so that it is not guaranteed to satisfy relation (1), and ambiguities may arise.

No matter which kind of technique is used, a filtering process to preserve phase details becomes a key step for an easier and more reliable phase unwrapping.

The widely used denoising techniques for images, for example convolution techniques or Fourier techniques generally produces over-smoothed images that may smear out discontinuities of wrapped phase fields, particularly in high frequency zones. Some denoising techniques have been developed for improving the phase unwrapping [3,4], for example we can find in the work by Kemao et al. [8] a comparative analysis of some methods. Recently, a more effective point of view for filtering wrapped phase maps has been pointed out by Tang et al. [9] who use sine/cosine filtering with windows along tangent directions of isophase contours of ESPI (electronic speckle pattern interferometry) phase maps. Even more recently, the same author proposed the oriented-couple partial differential equations [10] for denoising wrapped phase patterns. In both cases [9,10] the key idea is the filtering along isophase lines (i.e. along the orthogonal direction of phase gradient). This strategy have two big advantages: first, noise can be easily removed because phase information and noise are conveniently separated in the frequency domain, and second, discontinuities of the wrapped phase map are preserved, specially in high frequency zones.

Since the last three decades regularization methods have been widely used for image processing [11–15] which have

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0143-8166/$ - see front matter
doi:10.1016/j.optlaseng.2010.02.002