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Discussion

Comment on the paper: H.-E. Hwang, P. Han, Theoretical analysis for surface tilt and translation detection based on speckle photography in the Fresnel domain, Opt. Commun. 282 (2009) 351–354

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ABSTRACT

In a recent paper [H.-E. Hwang, P. Han, Opt. Commun. 282 (2009) 351] a speckle based metrology system is proposed which it is claimed provides significant advantages over existing systems. In this paper, we show that the discussion presented in [H.-E. Hwang, P. Han, Opt. Commun. 282 (2009) 351] is deficient, and that several of the statements made are incorrect and/or misleading.

1. Introduction

Recently Hwang and Han have proposed an optical system [1], which allows the simultaneous measurement of tilt and translation of a rigid surface. It is claimed that this new Fresnel Transformation (FST) based system, when compared to previously proposed systems (particularly Fractional Fourier Transformation (FRT) based systems), is: (1) more convenient and compact to implement and operate, (2) that experimental scaling errors can be avoided using it, and (3) that a time delay which occurs in all previously proposed FRT based system can be avoided, making the new system more accurate.

In this comment we point out that:

(i) We have previously presented a general theoretical analysis of such speckle metrology systems, based on the use of the Linear Canonical Transform (LCT), [2,3], of which both the FST and FRT methods are special limiting cases. We have also presented experimental results for such systems [2–4];
(ii) Suitable implementation and calibration of practical FRT based systems allows scaling related issues to be avoided. Such FRT systems can have significant advantages over FST based ones [5,6];
(iii) An experimentally implemented system, previously described by us in the literature [2,7], can be operated using a single camera without any significant time delay between image captures. Furthermore we indicate how the system described in [1] might be improved based on the implementation given in [7]; Finally we show that
(iv) The implementation of practical LCT measurement systems (including those described in [1] and [8–10]), require the use of speckle based correlation techniques instead of speckle photography fringe analysis. Any meaningful comparison of such systems requires an analysis of the evolution of the correlation characteristics of speckle fields between differing LCT domains [9,10].

2. Speckle based metrology

We now deal with each of the points (i)–(iv), raised in the introduction.

2.1. Novelty

The LCT is a general linear lossless transformation [11]. It describes the propagation of a scalar field in a paraxial optical system

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(Quadratic Phase System). When used in conjunction with the Collins ABCD Ray Matrix, and illustrated using the Wigner Distribution Function (WDF), it provides a unifying picture of optics in the paraxial regime [2]. Both the FST and the FRT are single parameter special cases of the three-parameter LCT (or five-parameter Special Affine Fourier Transform [11]).

In [2], the role of the LCT is clearly discussed, with the WDF used to provide illustrative clarification. In particular the sensitivity of such systems to any combination of ABCD parameter values is clarified and both the Fresnel and FRT are clearly noted as special cases. Experimental results are also reported. While [2] is referenced by Hwang and Han [1], it appears that the authors have misinterpreted and underestimated the full significance and precedence of the work therein. The FST based analysis presented in [1] is less general than the LCT analysis described in [2]. Furthermore since the FST based system is only verified using highly idealised numerical simulations, and contains no experimental results, the author cannot draw any reliable conclusions as to how it might perform in practise.

2.2. Advantages and disadvantages of the systems

In [1], the claim regarding the superiority of the proposed FST based system, over previous systems (particularly over FRT based systems), relies on several points.

(I) First it is noted that fewer optical component (thin lenses) are necessary to implement the system.
(II) Second the authors claim that scaling errors may result in a significant reduction in the accuracy of comparable FRT based systems.

In relation to Point I., while we agree that the FST based system, as proposed in [1], requires fewer lenses, than the FRT system discussed in Ref. [6] in 2003, the FRT system proposed in [7] in 2006 requires a single camera, data acquisition card, etc. Furthermore, as is discussed in Section 2.3, the system described in [7] only requires memory sufficient to deal with the two frames sequentially grabbed, as opposed to the four images which must be captured and processed by the system proposed in [1]. Since [7] is referenced in [2] the authors of [1] should be familiar with it and should have referenced it in [1].

However it is not sufficient to only consider hardware cost/space requirements when comparing systems. As is discussed in [2,5], measurement performance, i.e. both the minimum resolutions (the sensitivities), and the dynamic ranges, must also be carefully considered. In other words, once the system is built, what are the smallest and largest values, of tilt (angular rotation) and/or lateral in-plane translation, the system can measure without external adjustment?

In relation to sensitivity we have shown [2,5] that when using the FRT there is a clear interdependence, between the measured sensitivity to tilt and translation. In the image domain, i.e. FRT $\theta = N\pi$, where N is any integer, the system has maximum sensitivity to in-plane translational motion and is insensitive to angular motion. However in the case of the FRT based system it is also possible, when FRT $\theta = (2N+1)\pi/2$, i.e. a Fourier Transform, to make the system extremely sensitive to angular motion but completely insensitive to in-plane translational motion. A compact FST system cannot be implemented to achieve both of these limiting high sensitivities.

Furthermore we have also shown in our papers how a trade-off can be made, when using FRT based systems, between the dynamic ranges of tilt and translation measurement [2,5]. This trade-off depends critically on the speckle correlation characteristics of the field, but in general the higher the sensitivity to a measurement parameter change, the lower the dynamic range possible. Since a compact FRT based systems permits a wide range of sensitivities to be accessed, it also permits a tailoring of the inter-related sensitivities and dynamic ranges.

Much of the above discussion however is predicated upon the assumption that such comparisons are restricted to systems based solely on use of the FRT and FST. As noted in Section 2.1 this discussion has become moot since LCT based systems are used [2]. In this case extra degrees of freedom become available, eliminating the restriction imposed by use of the FST or FRT, allowing much greater measurement flexibility [2,4].

In relation to Point II., and the issue of scaling errors, we make two comments:

(a) In our experimental system implementations we use scale invariant optical FRT systems [7]. Thus our optical systems are simply implemented so as to avoid such error. Again however, as has been reported in the literature, once our discussion includes the use of LCT systems scaling issue can simply be avoided or indeed included in the design.
(b) Following careful implementation and calibration (see the experimental results presented, i.e. [9]), we believe that the fundamental limits on the performance of such systems will ultimately be determined by exactly the same sources of inaccuracy encountered when using the system presented in [1], namely hardware quality, and the ambient mechanical, electronic and optical noise.

2.3. Time delays, the number of cameras and the number of captured images

We have experimentally demonstrated several systems capable of measuring simultaneously the translations and tilts of rough surfaces using a single camera [2,7]. A novel and particularly compact metrology system based on use of the FRT is described in [7]. This system simultaneously captures, in a single image frame, the two optical FRTs (of different order) of the same input field. Two such frame grabs are performed, one at time t1 and once again at time t2. Correlating these two sequential images allows all in-plane translations and out-of-plane tilts to be independently estimated. We refer to the system as performing *mixed domain speckle metrology* [7].

The system described in [1] requires the use of two cameras placed to capture images in two different FST domains. Each camera must capture two images, one at t1 and one at t2, and then process the resulting four frames of data. Unlike the system proposed in [1], the dynamic range of our single camera is shared between the information in the two simultaneously incident speckle fields. However it should be clear that this system (if implemented using identical hardware to that proposed in [1]), will not operate more slowly or less accurately due to time delays.

2.4. Speckle correlation statistics

Speckle correlation techniques are critical to the implementation of such LCT based systems. In early work [12,13], in 2000, when we were primarily concerned to demonstrate the principle of our methodology, speckle photographic principles were employed. However, as is clearly indicated in our more recent work, while the magnitude of motion can be extracted by examining the period of the modulation of the speckle fields following processing, the direction of motion (sign) cannot be simply extracted in this way and remains unknown without some a priori information. In order to unambiguously extract both the amplitude and direction of the tilt or translation motion from the captured images it becomes necessary to apply correlation based techniques.

Only the use of correlation based techniques permits the use of the systems described in [2] and [7]. However once this fact is accepted, then in order to determine the operating resolution and dynamic range of the system [5,8,10], detailed knowledge of the statistical correlation properties of the speckle field (captured in different domains), becomes critical. The statistical properties of the fields depends not only on the wavelength of illumination and the roughness of the surface under examination but also on the positioning and size of the apertures used in the metrology system and the LCT domains in which we choose to capture our output images. In this regard the discussions and comparisons presented in [1] are deficient and potentially misleading.

Finally we note that by simply removing the lenses present in the two OFRT arms in system described in [7] an FST based metrology system; with many of the potential advantages of this single camera system, can be implemented. However, once again, the use of correlation techniques will be critical to ensure unambiguous operation.

2.5. General comments

When simulating speckle, the resulting speckle size also depends on the sampling rate with resultant implications for any simulation based analysis. For example, larger speckle makes it harder to determine precisely the edge of the periodic fringe modulation. Using standard numerical techniques to simulate Fresnel propagation [14] typically requires that the input matrix be padded before propagation in anticipation of the spreading of energy due to diffraction. Although this padding operation would be expected to have significant effects on the numerical results, it is not discussed in the manuscript. Furthermore, in all physical speckle metrology systems, decorrelation of the speckle fields occurs (due to motion of the object surface), and can be attributed in part to the finite size of the camera and apertures in the system. This effect has been described and experimentally demonstrated in [9] and would be expected to manifest itself here as a surface-motion-dependent reduction in fringe contrast. From a reading of the text [1] it is unclear whether such effects have been considered by the authors. A lack of clarity about these fundamental points raises questions about the usefulness of these simulations in ascertaining even qualitative system performance.

Finally while the references presented in [1] appear in general appropriate we note that: (i) two of the last three papers listed in the reference list are not cited anywhere in the paper; (ii) one of the author names given in Ref. [20], in [1], is misspelled; and finally; (iii) that several references, which we believe it would have been appropriate to cite, were not included. We refer the interested reader to the various reference lists in [2–14] noting in particular some recent contributions in this area by Fricke-Begemann [15] and Yura and co-workers [16,17]. Relevant speckle correlation issues have recently been examined in [18].

3. Conclusions

The discussion of speckle based metrology systems present in [1] is seriously deficient and misleading. In this comment we have described our most serious concerns and presented a brief overview of this area in order to reduce the potential for confusion.

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