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A Review of Some Recent Work in the Area of Imaging and Optical Signal Processing

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Abstract: A concise review is presented of research recently carried out within our research group. Topics discussed include: (i) Imaging through turbulent media using Lucky Imaging combined with synthetic apertures; (ii) Numerical algorithms and simulation of quadratic phases systems, i.e. the Fast Linear Canonical Transform, appropriate sampling, aliasing and the Wigner Distribution Function; (iii) Controlling speckle in such optical systems and speckle based metrology; (iv) Digital holographic systems and their application; and (v) Optical encryption and multiplexing.

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1. Introduction

In this paper I will try to very briefly introduce several research topics which I, collaborators and several current and former graduate students have been actively involved in studying. Most of the technical results below have already, or will soon appear in the literature, and a fairly thorough listing of our recent papers is provided to facilitate the interested reader [1-25]. One of the novelties of the presentation below lies in the overview provided. The other is the interconnections made between the various topics in Optical Signal Processing, (OSP).

Every research topic was informed by my and my co-authors shared backgrounds in Fourier Optics and the recent extension of these ideas using the Collins ABCD matrix, Linear Canonical Transform (LCT), Wigner Distribution Function (WDF) and what is sometimes referred to as Phase-Space Optics (PSO) [1]. Furthermore in every topic discussed below the development and use of numerical algorithms plays a crucial role in processing or interpreting the experiments performed. It is also fair to say that the algorithms themselves are developed to 'fit the physics efficiently' and that often in trying to achieve such an optimum fit interesting insights into the systems being examined and the models themselves emerge. Thus these tools and ideas provide a unifying picture which allows ray matrices, paraxial wave optics and the numerical simulation of such optical Quadratic Phase Systems (QPS) to be brought together in a systematic and insightful way.

2. Measurement: Phase, Motion and Speckle

A detailed overview of recent work in the area of PSO, to which we contributed, is given in [1]. PSO is an approximate phase space representation firmly grounded in the more physical WDF. While other such representation of signals exist and have been used to interpret optical systems, i.e., the Ambiguity function [2], the WDF and the PSO offer simplicity. Furthermore, with use they can provide intuitive insights and suggest practical applications. One such insight is that the phase of a signal can be retrieved without the use of interferometric techniques by capturing projections (marginals) of the same signals' WDF in different domains. To do this in [3] the Fractional Fourier transform, (FRT), distributions (intensities) for different FRT orders were imaged. Thus the FRT, which is a special case of the LCT, was used and the signal phase extracted experimentally. The effects of FRT orders, noise in the system and the spatial frequency response were quantified.

Based on another insight, provided by use of the WDF and LCT, it has been shown that simple Speckle Photography systems can be used to measure in-plane tilts and rotations by capturing two sequential images of the surface before and after motion [4,5]. Once again these images must be captured in different domains, i.e. the light had passed through different QPSs, undergoing different LCTs or ABCD matrix transforms. This sounds complex but can be understood very simply using the graphical techniques associated with PSO [4,5].

It was found necessary, when using such a speckle based metrology systems, in order to avoid ambiguity in relation to the direction of motion, to use correlation techniques. The measurement process, including the resolution and dynamic range of the system, thus depended critically on the speckle correlation properties. In order to design and interpret the results from such systems it was necessary to determine how the speckle evolved as it passed through apertures and through QPSs [6-9]. In our most recent work in this area we have shown how longitudinal and lateral speckle size depends on the aperture (shape, size) and varies on- and off-axis [10-11].

2. Fast Algorithms, Sampling and Aliasing

The Fast Fourier Transform (FFT) is a way of numerically calculate in $M \log N$ time the Discrete Fourier Transform (DFT), which requires a calculation time proportional to N^2 (where N is the number of samples being processed). The Fourier Transform (FT) is a very special case of the LCT, therefore it seems reasonable to ask whether a Fast LCT algorithm (FLCT) exists. It does and we have recently provided a very detailed description of such an algorithm in [12]. Given such a fast algorithm the selection of the number of samples N then become critical.

It is well known that the Space Bandwidth Product (SBP), i.e., the product of spatial extent of a signal by its spatial frequency bandwidth, can be used to estimate the number of regular samples (uniform sampling rate) necessary to meet the Shannon sampling criterion (i.e. the Nyquist rate). We note that once this rate of sampling is available the analogue signal can be extracted from the digitally processed representation. However real signals cannot be finite in both the space and spatial frequency domains and therefore replication and aliasing (overlap) occurs. These effects are well understood in Fourier Optics but are more complex to examine when using PSO.

The effects of compactness (finite extent) in various domains on sampling, and thus performing calculations, is explored in [13], while the rates of sampling used are further explored in [14,15]. Furthermore while the FLCT discussed above provides one approach to rapidly calculating the LCT of a signal, returning to the matrix description of such systems and decomposing the system ABCD matrix into the product of several sub-system matrices, other fast algorithms can be identified. The Fresnel Transform, (FST), is another special case of the LCT, and describes paraxial propagation in free space. For obvious reasons the FST has received a great deal of attention in the literature. At the moment it is of particular interest because of its use in processing Digital Holographic image data. Our approach has allowed us to re-evaluate one of the most popular decomposition based algorithms, the Direct Method of calculating the FST [16]. We have also been able to extend the PSO analysis in such a way as to allow us to re-interpret aliasing as related to the WDF cross terms produced by sampling [17].

3. Optical Encryption

There has been significant interest in encryption schemes which can be implemented optically [18-23]. Practical optical implementation of such systems is difficult [19,22] and the security and robustness of these systems is still a matter of study and analysis [18,20-23]. However not only do such systems pose a very interesting problem for the fast algorithms described above in Section 3, it has been shown that the problems of encryption and multiplexing can be discussed fruitfully using PSO [24].

4. Lucky Imaging with Synthetic Apertures (LISA)

In a recent paper [25] it was shown that combining the technique of lucky imaging with that of aperture synthesis advantages can arise, which allows atmospheric turbulence to be effectively eliminated over a large image field. Lucky imaging involves rapidly capturing many images and then selecting out some small subset of these images captured when at least some part of each image selected is close to being diffraction limited (minimally effected by the temporally fluctuating turbulence present). Aperture synthesis involves capturing images using sets of subapertures and then combining these in such a way that the diffraction limited image from a larger aperture is well approximated. By using smaller apertures the likelihood of capturing a lucky image increases. In [11] and [25] the effects of the size and separation of apertures, the criteria used to select lucky images, and the effects of Kolmogorov turbulence on the probability of capturing a lucky image and on the quality of the image produced have been examined. Work to date on LISA has been performed using purely Fourier Optics techniques.

5. Conclusion

Our work to date has raised many questions but also offered fruitful insights into possible applications of OSP.

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