PHASE SPACE METHODS FOR OPTICAL PROCESSING OF BIOMEDICAL INFORMATION

Tatiana Alieva*, Universidad Complutense de Madrid, Facultad de Ciencias Físicas, Madrid, España

ABSTRACT
The application of optoelectronic techniques, based on Fourier transform, bilinear distributions, fractional transformations, for biomedical information processing: filtering, segmentation and classification of biomedical images, characterization of optical manipulators, recovering of statistical tissue properties, is discussed.

Key words: Optical information processing, fractional transforms, bilinear distributions, optical manipulation, medical imaging

RESUMEN
En el trabajo se discuten la aplicación de técnicas optoelectrónicas basadas en la transformada de Fourier, distribuciones bilineales, transformadas fraccionarias para el procesado de la información biomédica: filtrado, segmentación y clasificación de imágenes biomédicas, caracterización de manipuladores ópticas, reconstrucción de las propiedades estadísticas de tejidos, etc.

INTRODUCTION

Nowadays optics is playing an important role in acquisition, processing and archiving of biomedical information. Special algorithms for analysis and classification of biomedical information are creating for computer processing of biomedical signals and images in order to simplify the feature extraction by clinicians and researchers. Within the foreseeable future telemedicine, automated screening and diagnosis are expecting to become common in everyday health care.

In biomedical information processing optics has certain advantages with respect to commonly used digital electronic computing due to its massive parallelism, operating with continuous data, possibility of fuzzy logic implementation and direct penetration into data acquisition process. Medical images usually contain large amount of information, which sometimes has to be processed in real time. The digitalization of the original analog image, obtained for example in radiography, often reduces the image quality. These facts underline the advantages of optical processing techniques: parallel processing and operating with continuous data. Moreover optical methods of information processing can be directly incorporated in the acquisition process in some optical modalities.

Note also that almost all typical tools applying in digital data processing can be implemented in optics [1-4]. Thus filtering and correlation operations can be performed by optical correlators, some joint phase space distribution such as WD and Ambiguity function, fractional transforms are actively used in optics. Optical wavelet transform can be applied to perform the multiresolution analysis. The fuzziness of typical optical phenomena such as diffraction and interference provide the possibility implement optical fuzzy logic. The holographic principles are applied for construction associative memories and neural networks.

The disadvantages of optical image processing systems mainly lie in low flexibility and programmability of optical systems, input/output problem and complexity of system maintain.

The application of optoelectronic techniques, based on Fourier transform, bilinear distributions, fractional transformations, for biomedical information processing will be discussed in this contribution.

OPTICAL FOURIER PROCESSING IN BIOMEDICAL IMAGE ANALYSIS

One of the principal operations used for the signal/image analysis is the Fourier transform. Optical implementation of this operation is based on the ability of a thin lens to produce the two-dimensional Fourier transform (FT) of an image on its back focal plane. The effectiveness and limitations of optical analog and digital methods for Fourier transform calculations applied for medical image analysis have been compared in [5]. It was concluded that both techniques are competitive.

The optical Fourier transforming systems are used for spatial frequency content analysis, or as a part of optical information processing system performing for example filtering and correlation operations.

E-mail: *talieva@fis.ucm.es

One of the possible applications of Fourier spectra is estimation of fractal dimension of biological structures. Optical examination of fractal structures was first proposed in [6]. Recently it has been proposed to characterize the fundus eye photograph by the slope of log log spectrum [7], which is related to fractal dimension. This approach makes possible optical analysis of fractal characteristics of retina photograph.

A typical optical scheme used for filtering or correlation operations includes the cascade of optical Fourier transformers. The filtering permits to extract the features of the medical images meanwhile the correlation allows to detect automatically the similarities of the compared images. The comparison of digital and optical correlators, made in [8], demonstrates the superiority of optical correlators in terms of parallelism and processing speed.

The disadvantages of optical image processing systems mainly lie in the complex structure of the required optical system and their small flexibility. Some steps have been done to create self-adaptive optical Fourier filtering system using photoinduced dichroism in a bacteriorhodopsin (bR) film [9]. The bR film produces the angular rotation of the polarization of the illuminating beam depending on its intensity. The combination of bR film and analyzer composes the filter set up which controls the pass of spatial frequency components. In particular application of this optical scheme for enhancement of the high frequency components of mammograms allows showing up the microcalcification clusters buried in surrounding tissue.

PHASE SPACE DISTRIBUTIONS IN OPTICS

Besides the FT operations phase space methods are widely applied in data processing such as phase retrieval, patterns recognition, filtering, signal and system characterization, texture discrimination, analysis and modeling of biological signals.

Phase space distributions provide information about the signal amplitude and phase in term of joint position and momentum representation and therefore localize in the framework of uncertainty principle a given temporal (or spatial) frequency in time (or space). The Wigner distribution (WD) is probably one of the better known phase space distributions. It was introduced for the application in quantum mechanics by Wigner in 1932 [10] but further was widely used in information processing and optics in particularly for the description of partially coherent fields. The WD of one dimensional signal is defined as

$$W(x,u) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \left\langle f(x+\tfrac{1}{2}x')f^*(x-\tfrac{1}{2}x')\right\rangle \exp[-i2\pi(ux')]dx', \quad (1)$$

where brackets stand for the case of nonstationary signal which is equivalent to partially coherence in optics. The WD is always real-valued but not necessarily positive; it preserves position and frequency shifts, and satisfies the marginal properties. Thus the projection of the WD in axis *x* corresponds to the instantaneous power and the projection on the frequency axis *u* to the Fourier power spectrum.

The WD is closely related to the canonical fractional Fourier transform (FT) [11, 3, 4], which is the generalization of the ordinary FT. The kernel of the fractional FT depends on the parameter α which can be interpreted as a rotation angle in phase space. The fractional FT of a signal *f*(*x*) for angle α is defined as

$$F_\alpha(u) = R^\alpha[f(x)](u) = \frac{\exp(i\alpha/2)}{\sqrt{i\sin\alpha}}$$

$$\int f(x)\exp\left(i\pi\frac{(x^2+\mu^2)\cos\alpha - 2xu}{\sin\alpha}\right)dx. \quad (2)$$

Thus for $\alpha = 0$ it corresponds to the identity transform, for $\alpha = \pi/2$ and $\alpha = 3\pi/2$ it reduces to the FT and inverse FT, correspondingly. Moreover $F_\pi(u) = f(-u)$. The fractional FT is continuous, periodic $R^{\alpha+2\pi n} = R^\alpha$, and additive $R^{\alpha+\beta} = R^\alpha R^\beta$ with respect to the parameter α. The inverse fractional FT is the fractional FT for angle $-\alpha$. The optical set up for the fractional FT for a certain α can be obtained from the conventional FT transformer changing equally the distances between the lens and the input/output planes. Note that the fractional FT systems are used for the shift-variant filtering, which is attractive for the processing of some biomedical images.

The squared moduli of the fractional FT, also called fractional power spectra, correspond to the projection of the WD upon the direction at an angle α in phase plane. The fractional power spectra play an important role in optics, because they are related to the intensity distribution at the output plane of the fractional FT system and therefore can be easily measured. The set of the fractional spectra for α from $[0, \pi]$ defines the Radon transform of the WD. The WD can be obtained from the set of fractional spectra applying the inverse Radon transform or other iterative procedure usually used in tomographic reconstructions. This is a basis for phase-space tomography [12] -a method for experimental determination of the complex field amplitude in the coherent case or mutual intensity for the partial coherent fields from the measurements of only intensity distributions. Application of the cylindrical lenses makes possible the reconstruction of two dimensional fields.

Other methods of reconstruction of the WD of spatial and time optical signals were proposed in [4, 13]. In particular the heterodyne method of WD measurements has been found very useful in the applications to optical coherence tomography. It was demonstrated that the mean square heterodyne beat signal, measuring in the real time, is proportional to the overlap of the Wigner distributions of the local oscillator and signal fields [13].

Wigner distribution, fractional FT are nowadays actively used in optics for description of coherence properties of light, beam design and characterization, shift variable filtering, encryption, design of neural networks. Some of these applications are also beneficial for biomedical information processing.

PARTIALLY COHERENCE LIGHT IN BIOMEDICAL IMAGING

Nowadays actively developed optical biomedical imaging techniques such as optical coherence tomography (OCT) [14,15] and optical coherent microscopy (OCM) [16], etc. use partially coherent light sources. OCT is a non-invasive, noncontact imaging modality for cross-sectional imaging of biological tissue with micrometer-scale resolution. OCT imaging is produced by measuring the intensity of backscattered light from internal tissue and the echo time delay applying the interferometry techniques. OCT was first used clinically in ophthalmology for the imaging and diagnosis of retinal disease and then was applied to image subsurface structure in skin, vessels, oral cavity, respiratory, urogenital, and gastrointestinal tracts.

In general biological tissues are mostly characterized by their statistical properties. The formalism of the WD is very useful for the description of coherence properties of light reflected from the tissues. It was suggested in [17] to create a novel OCT modality based on measurements of WD or its momentum width as a function of position in the tissue. The higher sensibility of the transversal coherence to the changes in scattering coefficient than the conventional OCT system that probes the corresponding change in the backscattering coefficient might lead to an improved contrast in the obtained images. The modified heterodyne optical phase space method proposed in [13, 18] allows simultaneously measuring of longitudinal and transverse coherence properties of broadband light sources, used in OCT.

Recently it has been shown that, by use of the spatial coherence properties of an incident field and a simple detection configuration, the two point correlation function of a random scattering potential can be determined [19]. The method, called variable coherence tomography, is based on collecting the scattered intensity along only one direction. In this method the incident beam which has a high degree of spatial coherence only between two points with desired variable separation is used. The phase space methods and in particular the WD can be applied for the design and characterization of these beams.

WD FOR BEAM CHARACTERIZATION

The qualitative characteristics of light beam are very important in biomedical applications were they used not only as cutting instruments but also for non-contact optical manipulation of mesoscopic systems, characterized by the length scales of 10 nm to 100 micrometers, forces ranging from femto- to nano-newtons and by the time scales upward from microseconds [20]. In biology, this range covers many of the inter- and intra-cellular processes responsible for respiration, reproduction and signaling.

The normalized moments of the WD are usually used for optical beam characterization. The low-order moments represent the global features of the optical signal such as total energy, width, principal axes, etc. Thus the second-order moments of the WD are used as a basis of an International Organization for Standardization standard of beam quality. The combination of the second-order moments describes the orbital angular momentum of the optical beam, used for the description of optical vortices. The application of vortex beams for optical trapping in biology is very promising [20]. In general there are $N = (n+1)(n+2)(n+3)/6$ n-th order moments. All moments can be expressed through intensity moments measured after beam transformation by passing through the first-order optical separable systems, for example fractional FT systems. It was shown [4] that in order to find all n-th order moments one needs N fractional power spectra, where $N = (n+2)^2/4$ for even n and $N = (n+1)(n+3)/4$ for odd n. Moreover N-(n+1) spectra have to be anamorphic.

NEURAL NETWORKS BASED ON THE FRACTIONAL FOURIER TRANSFORM

The high-level biomedical signal/image processing is related to the problems of data classification, model matching, linguistic description. The result of such interpretation may be a clinical diagnosis or understanding of some biological processes. These problems usually involve parallel processing of vast amounts of information. Since human beings (physician or researcher) are capable to solve these problems rather quick similar operations have been proposed for automatic decision making. They basically include Neural Network (NN) architectures, associative memories and fuzzy logic implementation.

Optical implementation of the NN offers the high number of neurons and interconnection density. Most optical NN uses free space interconnections.

Different configurations of the NN have been proposed [21]. Some of them can be considered as adaptive filters constructed by learning procedure. It was proposed to use the filtering in fractional FT domain to construct a one layer NN [22]. The two fractional FT operations represent two complex synaptic weights and linear summation. And the adaptively trainable filter plays the role of the nonlinear operator. For classification problems an additional sigmoid function may be used at the output. For the same number of input and output neurons, the fractional FT NN has much less adaptive elements and much simpler architectures than the standard perceptron. The architecture can be extended to multilayer configuration. It was shown that the NN using the fractional FT and mean square errors classifies patterns much better than similar one using original FT.

In general the selection of the input signal in the NN classification scheme is important for successful performance (minimal NN multilayer configuration, minimal error). The use of fractionally Fourier transformed input signals have been proposed in [23]. The appropriate fractional domain is selected by training for the best classification performance of the NN. The use of fractional FT pre-processing significantly improves the NN performance compared to both no pre-processing signals and pre-processing in FT. Note that the proposed configuration also can be implemented in optics.

Several beneficial applications of the NN in medicine have been already recognized. NNs are extensively used in diagnostic systems (detection of cancer and heart problems), biochemical analysis (blood and urine samples, track glucose levels), image analysis (tumour detection, texture classify-cation), drug development, etc. The appearance of the relatively cheap SLMs made the application of hybrid optoelectronic configurations in different areas including biomedicine very promising.

CONCLUSIONS

We have indicated only some directions of the implementation phase space tools used for optical processing of biomedical information. In reality there is a large list of powerful optical signal processing techniques which are directly incorporated in the information acquisition process or used for the processing of information obtained by different medical imaging modalities.

Optical biomedical data processing is especially beneficial if data are obtained by optical modalities and therefore processing system can be incorpo-rated in the acquisition set up or if similar treatment of big amount of images (for example mammograms) have to be done (then the flexibility of optical system is not crucial). Application of optical neural networks for biomedical information processing and develop-ment of optical data fusion schemes is an open area for future research.

ACKNOWLEDGMENTS

T. Alieva thanks the Spanish Ministry of Science and Technology for financial support of this research (“Ramon y Cajal” grant and project TIC 2002-01846).

REFERENCES

1. JAVIDI, B. and J. L. HORNER, eds. (1994): **Real-Time Optical Information Processing**, (Academic Press, New York).

2. LI, Y.; H.H. SZU; Y. SHENG and H.J. CAULFIELD (1996): Proc. IEEE **84**, 720.

3. ALIEVA, T.; M.J. BASTIAANS and M.L. CALVO (2001): **Recent Research Developments in Optics** 1, 105.

4. ____ (2005): “Fractional transforms in optical information processing,” **J. Appl. Signal Process**, to be published.

5. LI, Y. **et al**. (2002): **J. Biomed. Optics** 7, 255.

6. ALLAIN, C. and M. CLOITRE (1986) : **Phys. Rev. Lett. E 33**, 3566.

7. RODRIGO, J.A. **et al**. (2003): Annual OSA meeting "Frontiers in Optics”, Tucson, USA, 47, (5-10 October).

8. GHEEN, G.; E. WASHWELL and C. HUANG (1992): **Proc. SPIE** 1772, 96.

9. PANCHANGAN, A. **et al**. (2000): **Med. Phys**. 28, 22.

10. WIGNER, E.P. (1932): **Phys. Rev**. 40, 749.

11. MENDLOVIC, D. and H. OZAKTAS (1993): **J. Opt. Soc. Am**. 10, 1875.

12. RAYMER, M.G.; M. BECK and D.F. Mc ALISTER (1994): **Phys. Rev. Lett**. 72, 1137.

13. WAX, A. and J.E. THOMAS (1996): **Opt. Lett**. 21, 1427.

14. HUANG, D. **et al**. (1991): **Science** 254, 1178.

15. FERCHER, A. **et al**. (2003): **Rep. Prog. Phys**. 66, 239.

16. IZATT, J.A. **et al**. (1994): **Opt. Lett**. 19, 590.

17. YURA, H.; L. THRANE and P.E. ANDERSEN (200): **JOSA A** 17, 2464.

18. WAX, A.; S. BALI and J.E. THOMAS (1999): **Opt. Lett**. 24, 1188.

19. BALEINE, E. and A. DOGARIU (2004): **Opt. Lett**. 29, 1233.

20. GRIER, D.G. (2003): **Nature** 424, 810.

21. CAULFIELD, H.J.; J. KINSER and S.K. ROGERS (1989): **IEEE Proc**. 77, 1573.

22. LEE, S.Y.; and H.H. SZU (1994): **Opt. Eng**. 33, 2326.

23. BARSHAN, B. and B. AURULI (2002): **Neural Nets** 15, 131.