Frequency-domain processing in high-performing optical measurements

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Our capability to shift a signal of interest from its original frequency band to another one counts among the most powerful methodological tools indispensable to the efficient functioning of numerous devices involved in modern life; from the level of global infrastructural equipment down to every technological accessory owned by lay people. Such frequency-domain processing is essential to communication systems, signal multiplexing, modulation-demodulation methods, measurement instruments, data processing and noise reduction techniques and much more. Each time, our technological ability to build efficient sources, amplifiers, transmitters and detectors suited to a new frequency band has been generating new applications and devices allowing tremendous advances in diverse domains such as communications, transports, product manufacturing, medical instrumentation and research [1].

Optics has been playing a primordial role in this century-long history of knowledge and technology advancement. Indeed, the human eye provided an incredibly performing detector of visible light that allowed the early proposal of high level scientific explanations rooted in the empirical observation of diverse physical phenomena (such as diffraction, dispersion and interferences). Thanks to free-space propagation of light and imaging capabilities of the human eye, parallel signal processing has, for ever, been a natural attribute of human beings. The visible band of the electromagnetic spectrum was therefore investigated in a privileged way and optics has been a leading discipline in the advancement of scientific knowledge and, more generally, in the human understanding of the universe. For a few decades only, the different regions of the electromagnetic spectrum can be addressed through common, systematic and abstract formulations based on recent advancements in mathematical modeling and computational capabilities.

In the field of measurement also, the human eye capabilities permitted early instrumental realizations based on visible light, for instance telescopes and microscopes, but also efficient and low cost methods such as the Foucault knife-edge test that is still widely used for quality control of large-sized telescope mirrors. With respect to the frequency-domain, we may cite the Vernier principle that, by combining two grids with slightly different periods, allows the visual measurement of angles or lengths with extra resolutions far beyond the human eye capabilities. This is also the case of Moiré methods that allow sharp visual inspections through the qualitative analysis of low spatial frequency fringes produced by the relative correspondence between two gratings of higher spatial frequencies. More recently, optics has opened new possibilities in diverse domains requiring frequency monitoring; for instance in wavelength multiplexing applied to optical-fiber-based telecommunication systems or in highly-stabilized frequency reference signals through the generation of frequency combs from finely-controlled pulsed laser sources.

The different ways in which the frequency domain can be exploited for improving measurement capabilities are highlighted in the field of Optical Coherence Tomography (OCT) that proves to be very successful for biological tissue imaging. The basic principle of OCT is that of Fourier Transform Spectroscopy (FTS) that dates back to the late 19th century. The autocorrelation of a continuous light wave is obtained by slowly changing the optical path difference (OPD) of a two beam interferometer. Then, following the Wiener-Khintchine theorem, the power spectrum of the light source is given by the Fourier transform of the experimentally recorded autocorrelation function. First OCT setups (~1990) did reproduce the OPD scanning of FTS to record the set of autocorrelation functions associated to the different layers of the sample under test [2]. The key resolution element was therefore to have a short autocorrelation function which means a wide spectrum light source. Then, technical problems tied to speed and range of OPD scanning as well as sensitivity issues were circumvented by detecting the scattered light by means of a spectroscopic device based on a grating and a 1D image sensor. The depth response of the tissue is then obtained from a single recording by Fourier

Transforming the detected spectrum. The method is known as Fourier-domain OCT [3]. However, the technique is limited by the lower bandwidth of 1D image sensors (~100Hz) with respect to photomultiplier tubes or avalanche photodiodes. This state of fact induced new developments, especially that of swept laser sources of which instantaneous frequency is chirped at high speed (SS OCT). The signature response of the inspected tissue is then recorded within a few µs by means of a high SNR point-detector, thus allowing high speed volume imaging with dynamics close to 100 dB [3]. We may also cite alternative techniques in which the OPD scanning is performed without actual displacement by means of a diffraction grating used as recombining beam splitter in a Mach-Zhender interferometer configuration [4]. The example of OCT then highlights the diverse ways in which a same sensing signal; i.e. the light backscattered by a biological tissue, can be processed in different manners in the frequency domain in order to optimize measurement performances.

Another means to process light in the frequency domain lays in the use of diffraction gratings. In this interesting case, the spatial frequency of the grating does not affect the light frequency but its direction of propagation. Holography can be seen as a generalized form of diffraction grating. The averaged angle between the object and reference beams determines the mean spatial frequency of the grating-like fringe pattern recorded on the photosensitive layer of the hologram. However, because of light scattering on the object, the recorded fringe pattern is modulated by a stationary speckle pattern of which phase varies discontinuously from one grain to neighbor ones. This unpredictable stationary phase distribution of the recorded grating is responsible for the non-uniform diffraction of a reconstruction light beam that produces, as if by magic, the restitution of the recorded object.

In the last decades, the chemical processing of holographic plates has been circumvented by the development of Digital Holography that, despite the very small size of solid state image sensors, is proving to allow very efficient measurement tools in diverse application domains [5]. Digital Holography is also remarkable for the use of frequency domain methods for the computation of reconstructed holograms at different depths. The talk will highlight the use of frequency domain processing in digital holography from a specific application addressing micro-positioning needs in micro-robotics. In this application, the observed target itself is made of a pseudo-periodic pattern that is also designed for frequency domain processing in order to obtain highly-subpixel resolutions by means of phase interpolation [6, 7]. This approach, that transposes some interferometry methods to the field of computer vision, will be presented firstly in the frame of usual, refractive vision systems in order to highlight its unique capabilities in terms of spatial resolution, extended measurement range and multi-degrees-of-freedom measurement. The typical range-to-resolution ratio is about 10^6. The combination of this pseudo-periodic pattern visual method with digital holography expands these capabilities to an extended range of numerically-tunable working distances of more than 15 cm, compatible with below 100 nm resolution in lateral target positioning [8].

References:

1. Tonouchi, M. (2007). Cutting-edge terahertz technology. *Nature photonics*, *1*(2), 97-105.
2. Huang, D., Swanson, E. A., Lin, C. P., Schuman, J. S., Stinson, W. G., Chang, W., ... & Fujimoto, J. G. (1991). Optical coherence tomography. *Science (New York, NY)*, *254*(5035), 1178.
3. Choma, M. A., Sarunic, M. V., Yang, C., & Izatt, J. A. (2003). Sensitivity advantage of swept source and Fourier domain optical coherence tomography. *Optics express*, *11*(18), 2183-2189.
4. Froehly, L., & Leitgeb, R. (2010). Scan-free optical correlation techniques: history and applications to optical coherence tomography. *Journal of Optics*, *12*(8), 084001.
5. Schnars, U., & Jueptner, W. (2005). *Digital holography* (pp. 41-69). Springer Berlin Heidelberg.
6. Galeano-Zea, J. A., Sandoz, P., Gaiffe, E., Prétet, J. L., & Mougin, C. (2010). Pseudo-periodic encryption of extended 2-D surfaces for high accurate recovery of any random zone by vision. *International Journal of Optomechatronics*, *4*(1), 65-82.
7. Sandoz, P., Gaiffe, E., Launay, S., Robert, L., Jacquot, M., Hirchaud, F., ... & Mougin, C. (2011). Position-referenced microscopy for live cell culture monitoring. *Biomedical optics express*, *2*(5), 1307-1318.
8. Vergara, M. A., Jacquot, M., Laurent, G. J., & Sandoz, P. (2016, August). In-plane position and orientation measurement of a mobile target by digital holography. In *Latin America Optics and Photonics Conference* (pp. LTh3C-3). Optical Society of America.