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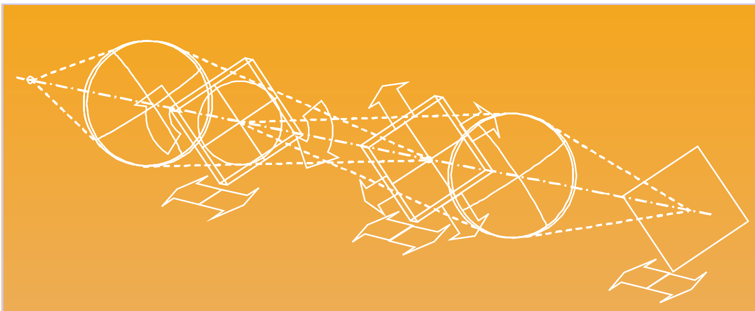
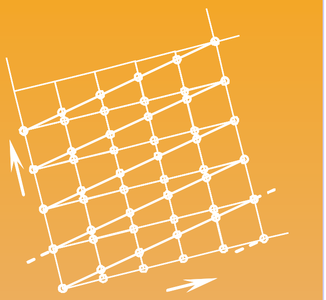
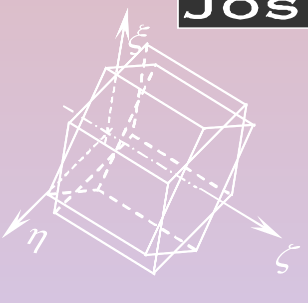
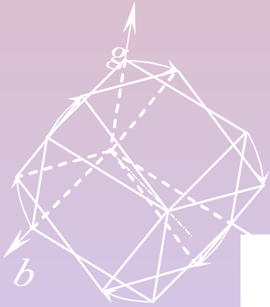
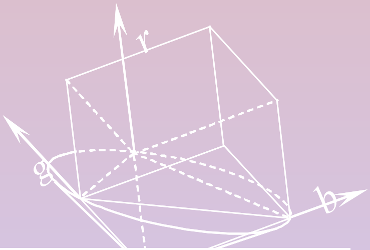



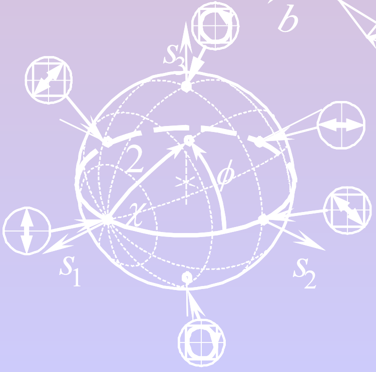
LIQUID CRYSTAL DISPLAY-BASED
OPTICAL PROCESSOR
FOR
COLOR PATTERN RECOGNITION
BY THREE-DIMENSIONAL CORRELATION

JOSEP NICOLÁS ROMÁN









MEMORIA PRESENTADA PER A OPTAR AL GRAU DE DOCTOR EN CIENCIES FISIQUES
BELLATERRA, NOVEMBRE 2002

Universitat Autònoma de Barcelona
Departament de Física

Doña María Josefa Yzuel Giménez, Catedrática de Óptica de la Universitat Autònoma de Barcelona, y Don Juan Campos Coloma, Profesor Titular de Óptica de la Universitat Autònoma de Barcelona,

CERTIFICAN

que Don Josep Nicolás Román, Licenciado en Ciencias Físicas, ha realizado bajo su dirección, y en el Departament de Física de la Universitat Autònoma de Barcelona, el trabajo *“Liquid-crystal device based optical processor for color pattern recognition by three dimensional correlation”*, que se recoge en esta memoria para optar al grado de Doctor en Ciencias Físicas.

Y para que conste, de acuerdo con la legislación vigente, firman este certificado en Bellaterra, a 10 de Diciembre de 2002.

Prof. M.J. Yzuel Prof. J. Campos

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Dedicado a la memoria de mi padre
José Nicolás López,

a mi madre,
a mi hermana Paqui.

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Chapter 1. Introduction

1.1. Introduction

The research developed in this thesis is within the framework of optical signal processing, and optical information systems. In particular, our research is focused on color pattern recognition and on the improvement of an optical processor working in real time, in order to implement optically in a single correlation, the processing of multichannel patterns.

Information processing concerns the detection, storing, transmission or processing of a physical measure, called the signal **[Réfrégier93]**. Historically, the development of signal theory and information processing has been associated to electrical and electronic engineering, and to digital computing. Nevertheless, since the invention of laser, and the development of holography **[Gabor48][Gabor49]** the research of information systems based on Fourier optics (or wave optics) has become a wide field in physics and engineering. Electronics and optical information systems were developed separately and there where no significant interactions between these two branches of science until the invention of computer generated holograms **[Lohmann67]**.

In the last 40 years, the race for circuit miniaturization and integration carried out by the silicon industry, has decisively contributed to the development of cheap, fast and efficient electronic systems, capable to perform most of the signal processing tasks. The high performance of these systems, their versatility, together with their low manufacture cost has promoted the raise of a huge market for information processing based applications.

Also optical information systems have been the object of an extensive research activity in the last years **[Leith2000]**. This way a number of differentiated topics have emerged. Examples of optical information technologies are optical communications, synthetic aperture imaging (SAR, lidar or sonar), holography and image processing systems and algorithms.

Nevertheless, the number of applications of optical information systems has been limited by the competence of microelectronics. Given the high performance reached by silicon technology, most of the signal processing tasks can be performed by a computer or a specialized electronic device, with efficiency enough to make unnecessary the use of an optical system. Although optical information systems perform the process in parallel, and in real time, they have been limited by the difficulty of introducing or extracting the information from optical signals on real time. Usually, the signal was introduced by a printed transparency or a hologram recorded on a silver halide plate, which were not able to be controlled on real time.

These factors have changed in the last years, the performance of microelectronic systems is reaching a physical limit that cannot be trespassed by the current silicon circuit miniaturization technology **[Keyes2001].** This has promoted the research of new strategies to keep increasing the performance of systems, among them the incorporation of optical technology. Clear examples of this are compact disc, and optical fiber communications. A fundamental key for the integration between electronics and optical technology has been the raise of opto-electronics. This technological branch has produced a number of devices that allow to generate, detect and control optical signals, we give some examples in Table 1.1. This way one of the major drawbacks of optical technology has been solved.

Device	Category
LED (Light emitting diode) VCSEL (Vertical cavity surface emitting laser)	Signal generator
MQW (Multiple quantum well) EOLM (Electro optical light modulator) LCD (Liquid crystal display) AOSLM (Acousto optic spatial light modulator)	Signal modulator
CCD (Charge coupled device) CMOS (Complementary metal-oxide semiconducor) detector	Signal detector

Table 1.1. Examples of optoelectronic devices for optical signal generation, modulation and detection.

On the other hand the extensive research on optical information systems, has matured many techniques that can now be incorporated to traditional information systems, from holographic memories to image compression systems. In conclusion, the integration of optical and electronic technologies has become a crucial component to keep on advancing on information technologies.

1.2. Optical correlators

Among the optical systems for information processing, we select the optical correlator as one of the research topics of this thesis. The use of optical correlators to perform pattern recognition tasks has been widely studied because of their ability to perform convolutions and correlations of images (large samples) in parallel. The working principle of optical correlators is closely related with holography, and with light diffraction. We illustrate this as follows. Let us consider the transmission hologram represented in Figure 1.1a. The hologram is illuminated by a plane wave (represented in the figure by one section of the wave), and introduces a distortion of the wavefront that at the focal plane of the second lens forms the image of the butterfly tabbed as B_1. The butterfly is centered at the image of the point source s_1 through the whole system. Let us also remark that the setup shown in Figure 1.1a is a Fraunhofer diffractometer, therefore the amplitude distribution $h(x,y)$ of the reconstructed image (the butterfly) is the Fourier transform of the amplitude distribution $H(u,v)$ just behind the hologram.

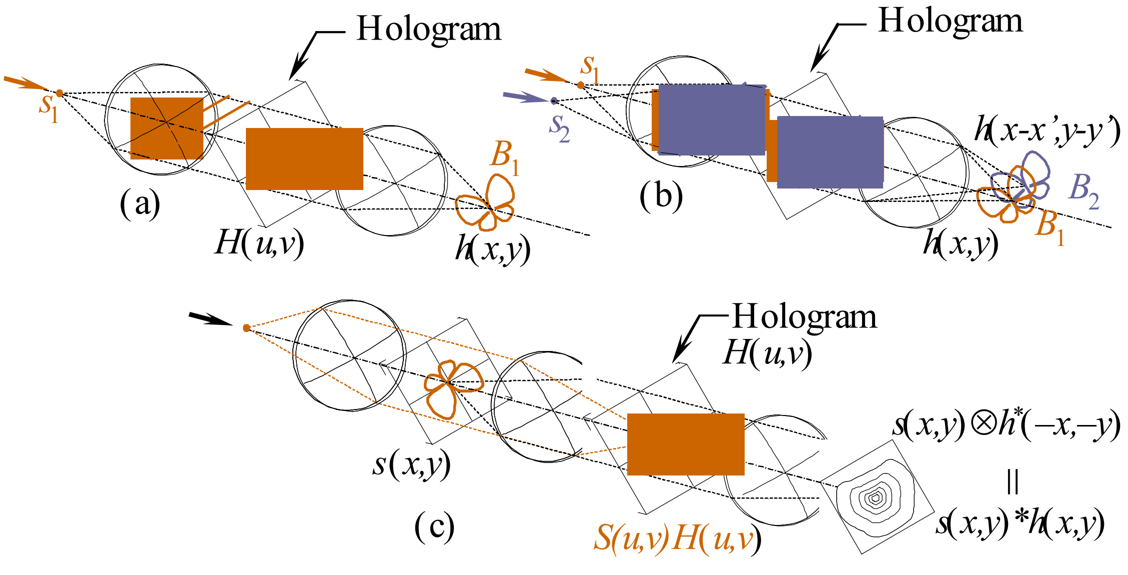

Figure 1.1. (a) Holography setup using one light source. (b) Holography setup using two light sources. (c) Optical processor.

Let us now consider that a second point source s_2 is used to illuminate the hologram, this is represented in blue in Figure

1.1b. This new point source generates an additional plane wave, with different orientation, that illuminates the hologram. The hologram introduces a distortion on the wave, so that at the focal plane of the second lens a butterfly appears, but now it is centered on the image of the source s_2 through the whole system (see B_2 in Figure 1.1b).

Because the optical system is linear, the response of the system to the two sources is the addition of the responses to each one of them. If the two sources are coherent each other the amplitude of the two responses must be added.

The same superposition principle can be extrapolated to the case in which instead of having discrete point sources, one has an extended source with amplitude distribution given by a function $s(x,y)$. This is the case of the Vander Lugt correlator **[VanderLugt64]**, represented in Figure 1.1c. Due to the linearity of the system, on can consider such a source as the contribution of a continuous ensemble of point sources, weighted by the function $s(x,y)$. At the focal plane of the second lens, for each one of these point sources, a reconstruction of the image encoded on the hologram appears, weighted by $s(x,y)$ and centered on the image of the point. This way, the amplitude distribution at the focal plane is the convolution $s(x,y)*h(x,y)$ between $s(x,y)$ and $h(x,y)$, or what is the same, the correlation between $s(x,y)$ and $h^*(-x,-y)$, let us say $s(x,y)\otimes h^*(-x,-y)$. Let us remark that also the first section of the correlator is a Fraunhofer diffractometer (see the red traces in Figure 1.1c).

This way, the amplitude distribution of the wave that illuminates the hologram $H(u,v)$ is the Fourier spectrum of $s(x,y)$ and behind the hologram, the amplitude distribution is the product of the Fourier spectra of $s(x,y)$ and $h(x,y)$. Then, one refers to $H(u,v)$ as the filter. This is in accordance with the convolution theorem, that states that the Fourier spectrum of the convolution of two functions is the product of their Fourier spectra. Equivalently, to obtain the correlation of the scene $s(x,y)$ with a reference function $r(x,y)$, the filter has to encode the complex conjugate of the Fourier spectrum of the reference function, that is $H(u,v)=R^*(u,v)$.

1.2.1. *The real-time convergent correlator*

The convergent correlator **[VanderLugt92]** is a modification of the 4F correlator that allows to change the scale between the scene and the filter. In this Thesis, we are going to use a convergent correlator working in real time, so a brief description is given here. We consider the setup described in Figure 1.2. The light at 458nm from an Ar^+ ion laser is focused onto the pinhole of a spatial filter. The pinhole is then the source, s, of a spherical wave that is focused by the first lens L_1 on the filter plane, at the image s' of the pinhole. The spherical wave, convergent on s', illuminates a liquid crystal panel (tabbed as scene SLM in Figure 1.2) in which the input scene $f(x,y)$ is displayed, and that modulates the convergent wave. In the image plane of the pinhole (s' in Figure 1.2), we place the filter SLM, that is another TNLC panel. The propagation of the light from the scene plane to the filter plane produces a diffraction pattern with the following amplitude distribution (see for instance, the detailed calculi given in **[Moreno96B]**):

$$A_S(u,v) = C\exp\left[i\frac{2\pi}{\lambda D}\left(u^2+v^2\right)\right]\cdot F\left(\frac{u}{\lambda D},\frac{v}{\lambda D}\right). \qquad (1.1)$$

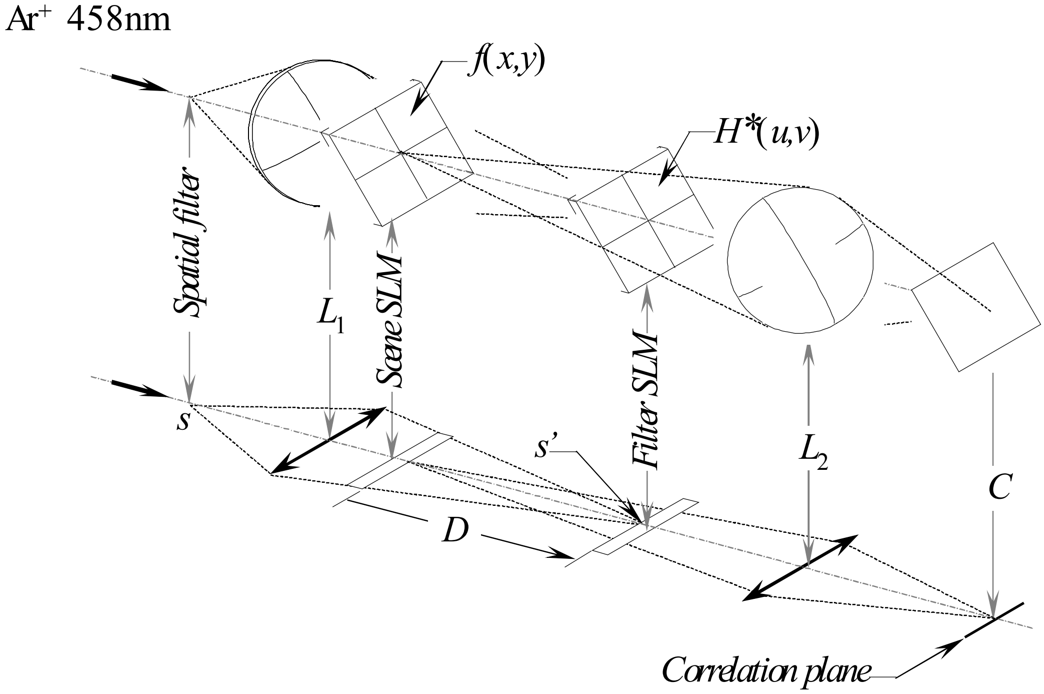

Figure 1.2. Scheme of the convergent correlator used in this Ph.D. Thesis.

Here u and v, are the coordinates on the filter plane, C is a normalization constant, λ is the wavelength of light, D is the distance between the scene and the filter (see Figure 1.2), and $F(u,v)$ is the Fourier spectrum of the amplitude distribution on the scene $f(x,y)$.

Equation 1.1 indicates that the Fourier spectrum of the scene, multiplied by a quadratic phase factor is obtained on the filter SLM. In addition, the scale of the Fourier spectrum of the scene on the filter plane depends on the distance *D* between the scene SLM and the filter SLM.

The filtered image of the scene SLM is focused onto the correlation plane (*C* in Figure 1.2) by a second lens (lens L_2). We can control the magnification of the scene on the correlation plane by changing the distances between the scene and L_2, and consequently the distance between L_2 and *C*. The amplitude distribution, in the correlation plane is given by:

$$A_C(x,y) = C_1 \exp\left[i\frac{2\pi}{\lambda C_2}\left(x^2+y^2\right)\right]\cdot[f\otimes h]\left(\frac{x}{\lambda C_3},\frac{y}{\lambda C_3}\right), \tag{1.2}$$

where C_1 is a normalization constant, C_2 is a scale factor determined by the focal length of L_2, the distances between the filter SLM and L_2, and C_3 is a scale factor determined by the focal length of L_2 and the distance between the scene SLM and L_2. Aside from a quadratic phase factor that does not concern the intensity distribution, the amplitude distribution at the correlation plane is the correlation between the function $f(x,y)$ displayed at the input SLM, and the impulse response function $h(x,y)$ of the filter $H^*(u,v)$ encoded on the filter SLM.

A large number of contributions have been made in the field of optical correlators since the first proposal in 1964. This research involves several aspects. Next we give a concise briefing of some of them.

1.2.2. *Design of optical correlators*

The above described 4F correlator[†] **[VanderLugt64]**, or the convergent correlator are not the only optical setups capable of performing the correlation between optical signals. The design of optical set ups capable of performing correlations has been vastly studied, and a number of modifications and alternative setups have been proposed, trying to optimize several aspects: flexibility, robustness, compactness or control.

A research topic on the VanderLugt type correlators design is the performance control. In **[VanderLugt67]** and **[Cai96]** a study of the effect of the misalignments of the optical set up on the correlation result is carried out. Concerning this, in **[Montes-Usátegui97]** an automated procedure is presented to correct some of the misalignments of the correlator at working time. The authors use iterative processes to correct the transversal misalignment of the scene or the filter caused by extreme working conditions.

Another goal in the design of optical correlators is to reduce the size of the optical set-up. Davis *et al* [**Davis89**] proposed to introduce a divergent lens between the scene and the filter of the convergent correlator. This way, the size of the diffraction pattern of the scene is determined by the distance of the virtual

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[†] The original correlator by VanderLugt is named 4F because the length of the optical system is four times the focal length of the used lenses.

image of the scene through the divergent lens, that can be longer than the physical system itself. In **[Juvells92]** the authors used a photographic teleobjective for the same purpose.

Another strategy to reduce the size of the optical correlator is to take advantage of reflections to fold the optical axis of the correlator, and to obtain free propagation paths bigger than the total bulk of the device. In **[Reinhorn97]** the authors propose to use planar optical elements and to let the light waves propagate confined by total reflection between the two surfaces of planar guides. The lenses and the signal modulation devices, are then placed on the surfaces of these planar guides. This way, compact and robust correlators can be constructed. A general approach in the design of compact optical correlators is given in **[O'Callaghan2001]**. The authors also propose a compact design based on the reflections on the sides of a beam splitter.

Aside from the different modifications of the original Vander Lugt correlator, a different set up for performing convolutions of optical signals was proposed by Weaver and Goodman **[Weaver66].** They proposed a set-up, known today as the joint transform correlator (JTC), in which both the scene and the reference are represented on the same plane of the optical system. This plane is then illuminated by a plane or convergent wave. The corresponding Fraunhofer diffraction pattern is registered on a holographic film or a detector. It contains the interference between the spectra of the scene and the reference. Then, this hologram is placed on the scene plane of the system, and the corresponding diffraction pattern has an amplitude distribution that contains the correlation between the scene and the filter. This set-up presents the advantage that it is more compact, and more robust to misalignments than the Vander Lugt type correlators. However, it presents difficulties because filters on Fourier domain cannot be implemented. In this case, the recognition performance is improved by applying non-linearities to the joint transform register **[Javidi89]** **[Réfrégier98]**.

1.2.3. *Optical signal modulators*

Another important research topic for optical correlation, is the kind of elements used to introduce the signal in the optical processor, namely the transparencies in which the image and holograms are represented.

The first works on correlators used silver halide plates. These plates provide high resolution, but present the drawback that they can not be controlled on real time. A number of technologies and materials have been developed in the field of spatial light modulators (SLMs), that is, in developing devices that can shape a light wave front by changing its phase or amplitude as a function of the coordinates in a plane **[Efron95]**.

Different goals are considered when developing spatial light modulators. The main aspects are the speed, the resolution, the diffraction efficiency and the modulation range. Next we describe briefly some of the most common technologies of SLMs.

a) Deformable Mirror Devices (DMD). These are devices in which each pixel is a small mirror, whose orientation can be switched between two orientations by a micro-electro-mechanical system (MEMS). Some authors have applied them in building optical correlators **[Florence89]**

b) Acousto-Optic SLM (AOSLM). They are based in the elasto-optic effect, by using materials whose refraction index depends on the applied forces. In these devices acoustic waves are used to produce an index pattern. Therefore they can be used as the scene or filter SLM in optical correlators**[Griffin94]** **[Davis2002]**.

c) Electro-Optical Light Modulators (EOLM): These are devices in which a material whose dielectric tensor, and therefore the index ellipsoid, can be changed by applying an electrostatic field .

d) Multiple Quantum Well (MQW) SLMs. These are devices composed by a large number of layers of different semiconductor materials. This structure generates a number of quantum wells for photons. By applying an external field, these barriers are distorted and then the transparency of the device can be changed **[Partovi93]**. These devices are extremely fast, they can change their state at speeds about 1 GHz. However, by now they are binary devices.

e) Photo-refractive materials. These are nonlinear materials whose refraction index can be changed very much by a relatively low intensity of light. This way, they have been lately used instead of silver halide emulsions. There are several kinds of photorefractive materials, inorganic crystals such as Lithium Niobate, polymeric materials (also known as photo-polymers), or biological materials such as the bacteriorhodopsin, that provides a very high resolution (5000 lines/mm) and fast response (<100μs) These materials can be used in volume holography, and therefore they can multiplex a large quantity of holograms by changing the wavelength or the incidence angle. A number of optical correlator designs take profit of this. **[Duelli97] [Thoma94] [Cook98]**

A special category of SLMs are those composed by liquid crystals. This is the most widely extended kind of SLM because of its commercial applications on displays and projection systems that make them easily available. Liquid crystals are materials that have a crystalline structure that can be distorted by a quite low voltage. By changing the crystalline structure one changes the polarization properties of the material. This way one can combine these SLMs with polarization devices to modulate the phase or amplitude of light. The transmission and phase modulation of the resulting systems are determined by the orientation of the molecules of the LCD, which can be altered by applying an electric field. Depending on the composition of the material, on the pressure and on the temperature these materials can be presented at different phases: nematic, cholesteric and smetic are the most usual ones **[Yeh99]**. Depending on the phase of the used material, one talks about the following kinds of SLM:

a) Ferro-Electric Liquid Crystal (FLC) SLMs. This is when the liquid crystal is in the so-called smetic C* phase. In this case, there are two stable orientations for the molecules, and when the applied voltage changes its sign, the orientation of the molecules changes by a certain angle. These modulators can reach speeds near 2kHz but they are binary devices. A number of works have been proposed to use these devices in optical processors **[Iwaki90]** **[Turner93].**

b) Twisted-nematic liquid crystal (TNLC) SLMs. This is when the liquid crystal material is in nematic phase. In this case, if there is no applied voltage, the molecules are oriented following a helical structure, but parallel to the sides of the SLM. When an external voltage is applied, the molecules tend to get aligned along the electric field. And this effect changes the polarization properties of the liquid crystal. This way, by using polarizers, a coupled phase and amplitude modulation is obtained. A number of contributions have been made to provide simple techniques to characterize the TNLCs **[Soutar94]** **[Davis99A]** **[Davis99B]**, as well as some simple physical models capable of predicting their optical behavior **[Lu90]** **[Coy96]** **[Márquez2000]** **[Fernández-Pousa2000]**. In addition these physical models have been applied to optimize the modulation response to the applied voltage as phase only modulation or amplitude only modulation **[Davis98]** **[Moreno98A]** **[Márquez2001A]**. These works consist on optimizing the modulation response of a system in which linear polarizers and retarder plates are combined with the TNLC. The configuration of these polarizing elements are explored to reach the best possible configuration in numerical simulations in which some of the configuration parameters are fixed.

Because of the low cost and the availability of TNLC panels, a lot of contributions have been in which these devices. are applied in optical correlators **[Pearson77]** **[Liu85]** **[Kirsch90]**, but also in diffractive optics **[Davis99]** **[Marquez2001B]**, or holography **[Stolz2001]**.

c) Parallel aligned (nematic) liquid crystal (PAL-LC) SLMs. These are also nematic liquid crystals. In this case there is not any helical structure, the molecules are always parallel each other, when there is no electric field they are also parallel to the sides of the liquid crystal cell, and when the electric field increases they tilt tending to align along the electric field. This reduces the effective birefringence of the device. This way, by using polarizing elements one can obtain, phase only modulation, or amplitude modulation **[Fernández-Pousa2001]** **[Mogensen2000]**.

1.2.4. *Signal encoding techniques*

The modulation introduced by the devices mentioned above is in general limited to amplitude-only modulation, phase-only modulation or coupled amplitude and phase. There is not, in general, a device that allows to control both amplitude and phase. This limitation has been overcome by the development of encoding techniques, that allow to encode complex valued functions in SLMs with limited modulation range. More precisely, these techniques allow to define functions, that taking only a limited range of values, have the same Fraunhofer diffraction pattern, in a region (or with some small deviation) as the fully complex valued function that one wants to encode. A variety of complex encoding techniques have been developed, depending on the modulation range of the SLMs.

Lohmann and Paris **[Lohmann67]** proposed a method to encode complex functions in binary amplitude only transparencies. Their method consists on encoding each pixel in an array of pixels, setting some of them to white and some of them to black. This way, the total amount of white pixels determines the amplitude, while the position of the white region within the array determines the phase. This encoding technique has a loss of resolution, what is equivalent to say that the binary hologram has a diffraction pattern identical to that of the encoded function in a limited region of the Fraunhofer diffraction pattern.

Lee **[Lee70]** and Burckhardt **[Burckhardt70]** proposed an alternative method, to encode functions losing less resolution than the Lohmann technique. However, his encoding technique needs a continuous amplitude only modulation regime. It consists on representing each pixel in three sub-pixels. This way, the three sub-pixels represent three different amplitude terms that contribute with different phase to the Fraunhofer diffraction pattern. The interference between these three terms is enough to represent any complex number with magnitude smaller than one. Again, the prize to pay is the resolution loss.

There are also techniques to encode complex-valued functions in phase only modulators. The double phase hologram **[Severcan73]** is a technique to encode the complex value of a pixel using two phase only pixels. The phase difference between the pixels determines the amplitude of the encoded function, and the average phase of the two pixels determines the phase of the encoded function.

Moreno *et al* **[Moreno97]**, demonstrated that binary amplitude phase only filters can be encoded in phase only filters, by applying a linear phase carrier in the zones with null amplitude, this way the light diffracted at these areas are moved out of the optical axis.

The encoding of full complex functions onto phase only modulators was proposed by Davis *et al.* **[Davis99A]**. In this paper, the authors propose to use a saw tooth phase grating as carrier, modulated by the amplitude of the encoded function. This way, the carrier shifts the encoded function (or its complementary to one) out of the optical axis.

All the encoding methods mentioned above, reproduce the Fourier spectrum of the encoded function exactly, in a limited region, in other words, they involve a spatial resolution loss. Different encoding methods allow to reproduce the Fourier spectrum in an approximate way, without spatial bandwidth loss. Some of these techniques are based on reproducing the value in the modulation range that better approximates the value of the encoded complex function. This is called the minimum Euclidean distance principle **[Juday93]**, and it can be applied for coupled amplitude and phase modulation regimes.

Another alternative was proposed by Cohn and Liang **[Cohn94]**. They proposed to add a random phase to the phase distribution of the encoded function. The statistical properties of the random phase are determined by the amplitude of the function. This principle can be applied for phase only modulation **[Hassebrook96]**, for ternary amplitude only modulation **[Duelli99]**, and also for coupled modulation **[Cohn98]**, or few levels of phase modulation **[Cohn99]**.

Other authors have proposed to combine two SLM with two different modulation responses to obtain full complex modulation range. This is done by projecting the image of the first SLM on the other SLM, with equal scale. This way, full complex modulation can be obtained by combining two different coupled phase and amplitude modulation responses**[Neto96]**, or by combining two amplitude only modulation responses, as the real part and the imaginary part of the complex function **[Tudela2002]**.

1.2.5. *Pattern recognition filters*

Another vastly explored field of research for optical correlators is the design of filters applicable to pattern recognition. As we have mentioned, correlators are optical systems capable of performing the convolution or the correlation between two two-dimensional distributions. The correlation between two functions presents a series of properties that allow its use for pattern recognition:

a) The autocorrelation (correlation of a function by itself) presents an absolute maximum at the origin.

b) The correlation is shift invariant. More precisely, the correlation is shifted by the same amount that the function. The sign of the shift for the correlation $f \otimes g$ is the same as for the function if the shifted function is f and the opposite if the shifted function is g. This way, if f is a shifted version of g, the correlation presents its absolute maximum at the location in f of the object represented in g, or in other words, it provides the location of the object.

c) The maximum of the squared magnitude of the cross-correlation between two functions, is always smaller than the product of their autocorrelation functions valued at the origin (their energy). That involves that the autocorrelation peak of a function is always bigger than the cross-correlation with any function with equal or minor energy. This way, one can distinguish a target from other objects because the correlation peak is the highest for the object to be recognized.

These three properties, and the ability of optical correlators to implement the correlation between two functions, give good reason for the application of correlation for pattern recognition techniques, that is, for target detection and for target location. However a number of improvements have been introduced for the optimization of the correlation as a pattern recognition technique. These improvements have been based on the design of Fourier frequency filters that can be introduced in the filter plane of an optical processor. Some criteria considered for the design of correlation filters are the noise robustness, the discrimination capability or the accuracy in the location, but also some convenient invariance properties: to rotation, to scale, to defocusing, or to perspective.

Vijaya-Kumar **[Vijaya90]** gave a set of parameters to qualify correlation filters according to some quality criteria:

a) Signal to noise ratio (SNR). Is the mean-energy to variance ratio for the autocorrelation at the origin. It is a measure of the noise robustness for the filter. The detection theory **[Réfrégier90A]** **[Guillaume97]** has demonstrated that the filter that optimizes this quality criterion (for zero mean additive noise) is the classical matched filter (CMF) **[VanderLugt64]**.

b) Horner efficiency (η'). Defined as the ratio of the energy at the correlation plane to the energy at the scene. It is a measure of the average intensity transmission of the filter. This parameter is important because it gives an indirect measure of the attenuation of the signal introduced by the filter, that is important because weak signals have bad SNR values. The optimal filter for Horner efficiency is the phase only filter (POF) **[Horner84]**.

c) Peak to correlation energy (PCE). It is a measure of the peak sharpness, that consists on the ratio of the energy at the origin to the total energy of the correlation function. For this quality criterion the optimal filter is the inverse filter (IF) **[Mu88]**.

d) Discrimination capability (DC). Defined as one minus the ratio of the cross-correlation energy to the autocorrelation energy of the target. It is a direct measure of the appropriateness of a filter to discriminate between two patterns.

The above mentioned filters, CMF, POF and IF, optimize one of the quality criteria but they have bad performance for the other parameters. This has given rise to some strategies that allow to optimize one of the quality criteria, keeping acceptable behavior for the other ones.

The fractional power filters (FPF) are an approach to this **[Vijaya90]**. These filters are obtained by dividing the Fourier spectrum of the target object by its magnitude raised to a fractional power ρ. This definition includes the IF, POF an CMF for ρ=2, ρ=1 and ρ=0, respectively. This allows us to optimize the value of ρ, that gives the better performance of a merit function that combines the different quality criteria.

Alternatively, Réfrégier proposed the optimal tradeoff filter OTF **[Réfrégier91]**, in which the filter expression is derived from its dependence on SNR, PCE and η'. This leads to a general expression, depending on two parameters, that permits to find an optimal tradeoff between the three mentioned quality criteria. That is to optimize one of the criteria without deteriorating the other ones. The author demonstrated that the OTF was a threshold of Wiener filters that take into account requirements for optical implementation such as the Horner efficiency.

Vijaya-Kumar and Bahri **[Vijaya89]** introduced the use of support regions to optimize the SNR for the POF without deteriorating the other quality criteria, like the PCE or η'. This idea was also exploited by Ahouzi *et al.* **[Ahouzi94]** **[Ahouzi98]** who designed binary amplitude phase only filters to optimize the DC, keeping acceptable values of SNR or η'.

Another goal pursued in the research of correlation filters is the invariance to distortions of the scene, that is, to design filters capable of recognizing the target object when defocused, rotated, scaled, or even seen from a different point of view.

A kind of rotation invariant correlation filters was proposed by Yang *et al* **[Yang82]**. It consists on representing the scene in radial components and selecting only one of its circular harmonic component (CHC) to design the correlation filters. A number of filter designs based on the circular harmonic expansion has been proposed since the proposal by Yang *et al* **[Hsu82]** **[Leclerc82]** **[Rosen91]** **[Gualdrón93]** **[Gualdrón96]**.

A more general approach to obtain invariant filters is the synthetic discriminant functions (SDF) approach **[Hester80]**. This is a formalism in which the filters are built starting from a set of images (the training set). The value at the origin of the correlation between the filter and the images in the training set is preset a priori. The SDF filter is the solution of a linear equation system composed by the expressions that come from identifying the correlation of the filter with each one of the functions on the training set, to its corresponding value. The solutions to the equation system depend on a number of free parameters that can be determined following some quality criteria. According to the chosen quality criterion for determining these free parameters, different SDFs are obtained.

The minimum average correlation energy (MACE) SDF is a filter in which the PCE is optimized **[Mahalanobis87]**. This way one minimizes the energy of the sidelobes on the correlation plane. The limit of the MACE filter when the training set is composed by only one image leads to the inverse filter (IF).

In other hand, if the chosen quality criterion to determine the free parameters of SDF is the SNR, one obtains the minimum variance SDF (MVSDF) **[Vijaya86]**. This filter is the generalization of the CMF.

Finally, one can establish a trade off between SNR and PCE to design a SDF. This leads to the optimal tradeoff SDF (OTSDF) **[Réfrégier90B]**, which is the generalization of the OTF for a training set of more than one image.

The main advantage of this formalism is its flexibility, because it can provide invariance to transformations even when there is no analytical expression for the distortion.

Most of the research reported above involves filter design in Fourier domain. This way, these filters are applicable in VanderLugt type correlators, but they are hardly implemented in a JTC. However, a different strategy, based on applying non-linearities to the acquired Joint Spectrum, has been widely exploited to improve the performance of the JTC for pattern recognition **[Javidi89A]** **[Yaroslavsky97]** **[Réfrégier98]** **[Ledesma98]**. Also rotation invariant filters **[Chang96]**

[Chang97], trade-off filters **[Réfrégier94]** or synthetic discriminant functions **[Javidi89B]** have been adapted for the JTC.

1.2.6. *Applications of correlators*

Optical correlators, and pattern recognition by correlation have given rise to many applications in different fields of information processing.

One of the more immediate applications of optical correlators is to track an object, taking advantage of the inherent speed and parallel processing characteristics of optical systems. This way, a number of applications based on target tracking by optical correlation have been developed, for traffic control **[Hao2002]**, for spacecraft navigation **[Chao2002]** **[Rollins2002]** or defense systems **[Busarow2000]**.

Nevertheless, the ability to determine the position of an object in an image, on real time, allows to track the movement of the object. This has also applications in image restoration for images deteriorated by vibrations or other movements of cameras **[Guillaume98]** **[Zhou2002]**.

Other applications in image restoration take advantage of the ability of optical correlators to perform convolutions (and deconvolutions) on real time. This way one can correct non-fixed aberrations, such as those produced by atmospheric turbulences in astronomical images **[McAulay2000]**.

Another field of application of optical correlators are security systems, to encode and decode information. **[Javidi94]** **[Javidi96]** **[Javidi98]** **[Javidi2000]** **[Unnikrishnan2000]** **[Abookasis2001]** **[Kim2002]** **[Chang2002]**, Usually the target image is convolved or deconvolved with a random function using an optical correlator.

Another feature of optical correlators is their capability of discriminating between optical signals. This fact gives rise to a number of applications in optical signal transmission, processing and storage. This way, optical processors are used to recognize the network address of all-optical packets in optical networking for communications **[Widjaja2001]**, and also to perform optical signal switching. Aside from these applications in signal transmission systems, there are applications also in optical storage and information processing. Holographic memory systems, use optical correlation to address the different memory pages, on real time **[Burr99]**. In addition, some quantum computing algorithms, (if they do not require entanglement) can be implemented in an optical correlator **[Bhattacharya2002]**.

1.3. Color pattern recognition

The spectral[†] distribution of the different points of a color image contains information that often is relevant for recognition purposes. As a matter of fact, objects that cannot be distinguished in black and white images are easily discriminated when their color distribution is considered **[Yzuel94] [Guillaume97]**. That is, when one considers the spectral distributions of the different points of the image. In addition, the color distribution of images sometimes contains information on the chemical composition of the objects present in the image. This is the working principle for many tele-detection technologies, from the spectroscopy of stars, to meteorological and climate survey satellites. Also in medicine and chemistry the identification of substances is often based on the color of the sample, dyed with different reactive agents.

This represents a motivation for introducing the color information in image processing systems. An example of this is the case of the human visual system (HVS), that in general has different responses for different spectral distributions, and gives rise to the sensation of color. However, because it only considers three different types of color detectors, only a part of

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[†] Here, the term spectral refers to the spectral distribution of electromagnetic radiation. that is, to the wavelength distribution of light, and not to the spatial frequency distribution obtained by applying the Fourier transform to the image.

the spectral information is considered, what gives rise to the phenomenon of metamerism.

According to this, in the last years a variety of proposals have been made to introduce the color information of the images in pattern recognition tasks by optical correlation. Additionally, some works on filter design for color pattern recognition have been proposed for these color image processing techniques. Some of them are the generalization of well known filters for monochromatic images, but some others are specifically designed for color pattern recognition.

In 1984, Francis Yu **[Yu84]** **[Yu86]** proposed a polychromatic correlator, in which the illumination was composed by three coherent beams, corresponding to the three primary colors: red, green, and blue. The diffraction pattern corresponding to each channel of the image where separated at the filter plane with a linear grating placed after the scene. This way, a filter could be adapted for each channel. The correlation corresponding to each channel is obtained in parallel, and the peaks on the correlation plane take the color of the recognized object (if it is a monocolor object). In summary, the authors propose a multi-channel correlation process, in which each channel is processed separately, and the result is combined at the end to produce a new color image. In addition the process for the different channels is multiplexed in the same optical processor, taking advantage of the fact that different wavelengths do not interact each other. Other authors have exploited the idea of wavelength multiplexing in optical correlators **[Case79]** **[Barbé99]** **[Esteve-Taboada2000]**.

The use of a multichannel JTC has also been exploited in color pattern recognition, either by using one color LCD **[Yu94]**, or by using three LCDs where the RGB components of the color image are displayed**[Alam2001]** **[Hsieh2002]**.

Multi-channel correlation has become a popular method for introducing the color information in the recognition process **[Millán89]** **[Attaleb99]** **[Guillaume97]** **[Caulfield97]**. An scheme of multichannel processing of color images is represented in Figure 1.3. The channels of the color image are extracted and processed separately, in a monochromatic correlator. Finally, at the end of the process, the results for the three channels are combined by means of some logical or arithmetic operation.

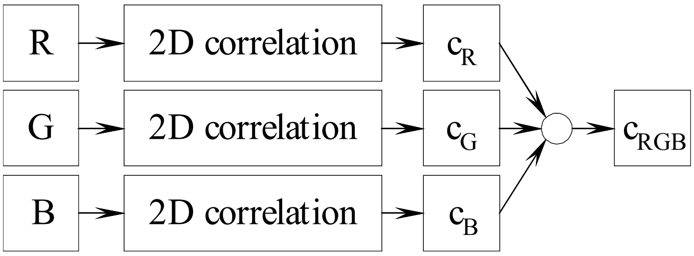

Figure 1.3. Scheme for Multi-channel correlation.

This way, Millán *et al* proposed to perform CMF and POF correlation for each one of the channels, and then to combine the results by means of the AND logical operation **[Millán89]** **[Campos91]**. That is, the color object is recognized as the target when the correlation peak exceeds a given threshold for all the channels. A variety of strategies to solve different problems of color pattern recognition are proposed. These include the case in which objects with equal shape and different color must be distinguished, and also the case in which a object must be recognized regardless of its color. The corresponding experimental results were given in **[Ferreira92].**

In **[Millán92]** the authors face the problem of character recognition regardless of the color of the character and the background. To do this for each channel of the target, two filters are used. One matched to the channel in direct contrast and the other in inverted contrast. The results for the two operations of each channel are combined by the OR operation, and then the results for the channels are combined by the AND operation. In another work **[Millán93]** the CMF and POF filter were combined with high pass and low pass filters so as to improve the discrimination between objects.

Since the first works in color pattern recognition, some improvements have been achieved. Some of these improvements come from combining the color channels before performing the spatial correlation. In Figure 1.4 we represent schemes for several strategies for the combination of color channels before the spatial correlation is performed.

The scheme in Figure 1.4a represents the scheme in which the three channels of a RGB color image are encoded in a single monochromatic image that encodes, in complex values, the color content of the image **[Badiqué88]** **[Thornton95]** **[McCabe2000]**. In **[Thornton95]** the saturation is encoded in the magnitude of the complex number, and the hue is encoded in its argument, however, the intensity information is discarded. To solve this problem, the same approach was extended by encoding the RGB channels using quaternion-valued pixels. This way, the three imaginary parts of the quaternion represent the red, green and blue components of the image.**[Sangwine96]** **[Sangwine98]**. The encoding presented in these works are only applicable to color images with three channels, and they are difficult to generalize to an arbitrary number of channels.

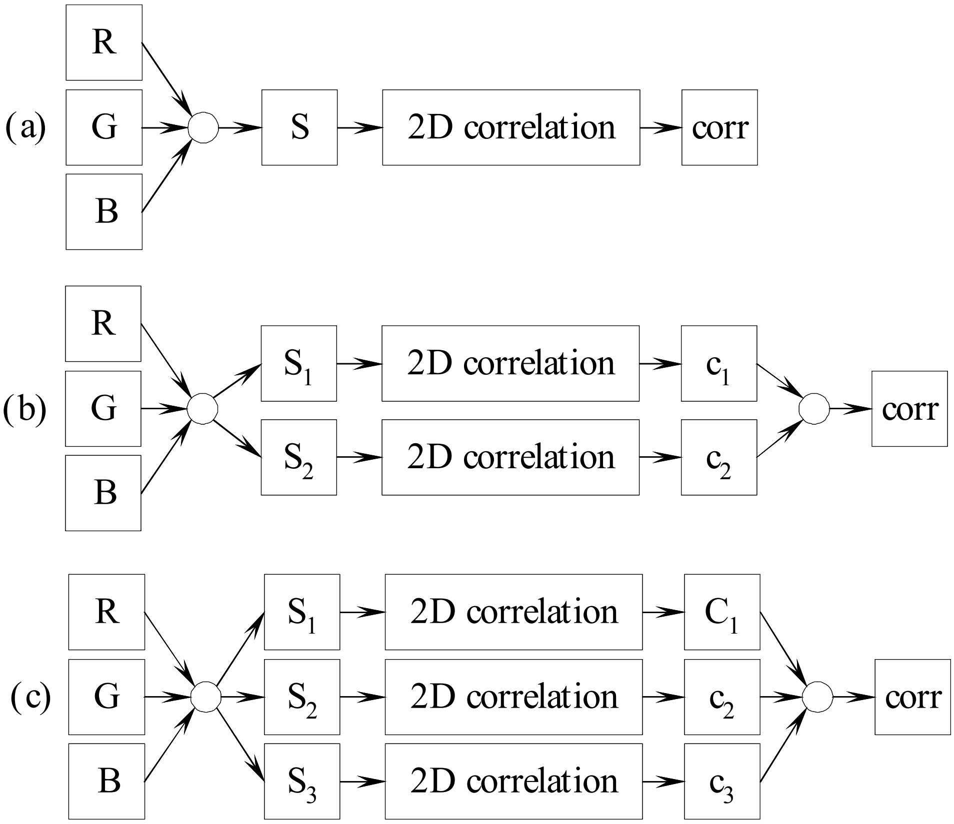

Figure 1.4. Schemes for scene preprocessing multichannel correlation (a) the three channels are combined in one channel, (b) in two channels, (c) in three channels.

A different approach is represented in Figure 1.4b. In this case the original RGB channels are combined in two channels that gather the information relevant for pattern recognition. In this sense some colorimetric transformations based on the Hurvich-Jameson model of the visual system were proposed **[Yamaba93]**. Also the ATD channels of the human visual system **[Millán95]** or the CIELAB coordinates **[Corbalán2002]** were used as the channels for the multi-channel correlation. These proposals present, among others, the advantage that they provide good recognition results by using only two channels and therefore reduce the overhead of the recognition process.

In Figure 1.4c we present a different criterion to combine the color channels of images. In this case the channels are combined considering the optimal transformations for target recognition and detection **[Yaroslavsky97]**. These transformations **[Moreno96A]** **[Kober97]**, lead to new multi-channel images with the same number of channels as the original image (Scheme in Figure 1.4c), but now they are orthogonal each other, what implies an improvement of the discrimination capability. The transformed channels, are real valued, but they take positive and negative values, nevertheless they can be implemented in an optical correlator **[Moreno98B]**.

1.4. Goal of this Thesis

In this Thesis we propose a novel correlation technique for color pattern recognition in which color images are described by three dimensional functions. We also provide new techniques for improving the performance of a real-time optical processor, that are essential to implement optically the proposed correlation methods successfully.

The proposed description of color images by three dimensional functions permits to process all the color channels as a unique signal which contains all the spatial and the color information of the image. We will provide the formalism for the description, the interpretation of the corresponding Fourier spectrum and we will study some filtering operations.

To enable the optical implementation it is necessary to characterize, to control and to optimize the response of the spatial light modulators used to introduce the input signal and the applied frequency filter. We try likewise to control the alignment of the optical system, which is known to be critical for the good performance of the system.

The optical correlator built meeting the mentioned considerations is used to implement several variants of a novel proposal for the encoding of the three dimensional correlation, and the designed filters.

The study will be carried out in the three following stages:

a) To provide a formalism to describe color images by three dimensional functions. That is, to define and interpret the three dimensional functions, and the corresponding Fourier spectra, as well as studying the filtering operations, and the correlation.

b) To build a real time optical correlator capable to perform the optical correlation of amplitude-only scenes, or phase-only scenes, and phase-only filters. We will optimize the modulation response of the spatial light modulators and we will develop an alignment procedure for the elements of the correlator.

c) To develop a technique that permits the implementation of the three dimensional correlation defined for color images in the optical correlator built according to point b).

1.4.1. *Three dimensional functions for describing color images.*

We will define three dimensional functions to describe color images. Two variables will indicate the spatial coordinates, and the third variable will indicate the spectral distribution at the point indicated by the spatial coordinates. In general one deals with images acquired with CCD cameras, this way the spectral information of images is reduced to a finite number of color channels. In particular we will consider the case of images with three color channels in the visible range, that is, RGB color images. Given the special characteristics of the color dimension of images, we will define and interpret the Fourier transform operation applied to the color distribution. In addition, we will give the interpretation of alternative representations of color space, like hue, saturation and intensity in the Fourier spectrum of color distributions. We will give a classification of the linear filtering operations for the three dimensional Fourier spectrum of color images, and we will relate them with the corresponding effect on the color image. Finally, we will design and interpret correlation filters for the three dimensional Fourier spectrum of color images so as to improve quality criteria such as the discrimination capability.

1.4.2. *The optical correlator*

We will characterize two liquid crystal panels so as to use them in the correlators to introduce the input signal (the scene) and the frequency filter. The used panels have, in principle, a coupled amplitude and phase modulation response to the applied voltage. In order to have amplitude only modulation, or phase-only modulation, we will develop a response optimization algorithm based on the use of elliptically polarized light. We will apply the optimization algorithm to obtain the desired modulation responses. Both amplitude only and phase only modulation configurations will be optimized for the input scene modulator. The configuration of the filter panel will be optimized to obtain phase only modulation, which is necessary for the filters we are going to implement in this Thesis.

The proposed architecture is a convergent VanderLugt correlator, because it permits the direct filtering of the frequency spectrum of the input signal. This architecture presents strict alignment requirements. Therefore a procedure to verify and quantify the alignment of the different elements that compose the correlator will be developed. The developed procedure will be based on frequency filtering tests and consist on the interpretation of the light distribution at the correlation plane, so as to avoid to incorporate new devices to the optical processor.

1.4.3. ***Optical encoding three dimensional correlation.***

Although optical processors perform operations with two-dimensional signals, in this Ph.D. Thesis we propose to optically encode linear operations between three dimensional signals, such as the three dimensional functions that represent color images or hyper-spectral images. We will study different variants of the proposed encoding technique, and we will study how the three dimensional Fourier transform and the three dimensional correlation are encoded by these variants. We will take into account the alignment and bandwidth requirements of the different variants of the encoding method, and we will use them to encode the different filters designed for color pattern recognition on the correlator.

1.5. Outline

Next we detail the outline of this Thesis, which is composed of seven chapters.

The research developed to improve the correlator constitutes the first part of this Thesis report. It covers Chapters 2 and 3.

In Chapter 2 we face the optimization of the modulation of the twisted nematic liquid crystal spatial light modulators (TNLC-SLM) used to introduce the scene and the filter. We study the relation between the polarization behavior of the TNLC panels and the phase and amplitude modulation of polarization states. Then, we perform the optimization of the configuration of the polarization elements to obtain either amplitude only modulation or phase only modulation. The results obtained in this chapter are reported in **[Nicolás2002B]** and in **[Nicolás2002E].**

In Chapter 3 we propose a procedure to control the alignment of the SLMs in the optical correlator. First, we detail the elements that must be controlled to obtain a correct match between the frequency filter and the Fourier spectrum of the input scene. Then, we propose a sequential procedure to align these elements and a series of tests to control them by simply observing the image at the correlation plane. We propose tests both for correlators in which the scene is encoded in amplitude only modulation and also for correlators with the scene working in phase only modulation regime. The results obtained in this chapter are reported in **[Nicolás2002A]** and in **[Nicolás2002D].**

The second part of this Thesis Report concerns the processing of color images by describing them using three dimensional functions. This part covers Chapters 4 and 5.

In Chapter 4 we introduce the third dimension of color images, which contains the spectral information. We extend the Fourier transform and correlation operations to these kind of functions. We also give an interpretation of the resulting Fourier spectrum. Because of the special nature of the color dimension, we pay special attention to the color Fourier transform and correlation only along the color axis. That study leads us to an interpretation of the color Fourier spectrum (obtained by performing the Fourier transform operation along the color axis) in terms of colorimetric magnitudes. Part of the results obtained in this chapter are reported in **[Nicolás2000]**

Once the description of color images by three dimensional functions is introduced, we study in Chapter 5 the filtering operations on the three dimensional spectrum of color images. First, we consider linear and nonlinear filtering operations of the color Fourier spectrum, including correlation operations. Then we extend this study to three dimensional spectrum of color images. Part of the results obtained in this chapter are reported in **[Yzuel2001]** and in **[Nicolás2003]**

The third part of the research developed in this thesis is reported in Chapter 6. In that Chapter we propose a method to encode the three dimensional correlation in an optical processor. We study how to encode a three dimensional function in a two dimensional function in a way that its two dimensional Fourier spectrum encodes the three dimensional spectrum of the encoded three dimensional function. We show how the proposed encoding technique is also suitable for the correlation of three dimensional signals.

Once the encoding technique is defined, and implemented in numerical simulations. we propose the implementation of the three dimensional correlation in the optical processor built as described in the first part of this Ph. D. Thesis report. We provide experimental results for different three dimensional correlation filters. The comparison of the experimental implementation with the numerical simulation is shown, as well as the improvement of the performance of the recognition of color objects by three dimensional correlation. Part of the results obtained in this chapter are reported in **[Nicolás2002C]**

Finally, the conclusions of this Ph.D. Thesis are summarized in Chapter 7.

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