Chapter 7. Conclusions

In the first part of this Ph.D. Thesis we have studied the optical correlator. We have performed the optimization of the modulation response for both the scene SLM and the filter SLM. We have also proposed an alignment procedure for the correlator. In the second part of the Thesis we have proposed and studied the description of color images by means of three dimensional functions, and we have defined the Fourier transform and correlation for this kind of signals. Finally, in the third part of the Thesis we have implemented the three dimensional correlation of color images in the optical processor. The obtained results lead to the following conclusions:

- ✧ A formalism based on the description of Jones vectors by means of Dirac brackets has been introduced. The proposed formalism permits to separate the wave information from the polarization state information carried out by a Jones vector. The operators corresponding to different polarizing elements have been given for the proposed formalism.

- ✧ The introduced formalism has been used to prove that the amplitude and phase modulation of spatial light modulators depend only on the polarization state generated at the input side of the panel and the polarization state detected at the output of the panel. The expression of the modulation as a function of the four free parameters that determine these polarization states has been given.

- ✧ The representation of polarization states in Poincaré's sphere has been used to establish the relation between the polarization states and the polarization state generator and detector used to generate or detect these states. The retardance requirements of the retarder plates used in the optical systems have been determined.

- ✧ The developed formalism has been applied to optimize the modulation of the liquid crystal spatial light modulators used in the optical correlator. We have defined a merit function to evaluate the quality of the modulation response of the spatial light modulator as amplitude only operation curve. We have also defined a merit function for the phase only modulation regime.

- ✧ An iterative algorithm for the optimization of the merit functions has been proposed. This algorithm is capable of obtaining the absolute maximum for the merit function, and not only the local maxima. We have used the proposed algorithm to obtain the polarization states at the input and the output of the liquid crystal panel that optimize the modulation of the spatial light modulators of the correlator. We have obtained the solutions for amplitude only modulation for the scene SLM, and the solutions of phase only modulation for both the scene and the filter SLMs.

- The configuration of the polarizing elements that generate and detect the optimal states have been obtained. These configurations have been implemented in the optical correlator and the corresponding operation curves have been calibrated.

- A procedure based on simple scene and filter tests have been proposed to perform the alignment of the optical convergent correlator for either amplitude or phase encoded scene. All the alignment sequence is based on the observation of the reconstructed image of the scene in the correlation plane and the interpretation of the effects of the filtering.

- The tests we have proposed permit the focusing of the diffraction pattern of the scene on the filter plane, as well as the centering of the filter, the alignment of the azimuth between the scene and the filter SLMs, and the scaling of the Fourier spectrum of the scene on the filter plane.

- The proposed tests constitute a series of objective criteria for the alignment of the correlator, in the sense that experimental observations are interpreted in accordance to a simple frequency filtering theory. For all the tests we have presented, experimental results that demonstrate the correct alignment of the optical correlator have been given. We have shown that the proposed tests constitute a good method to solve the main drawback (the alignment requirements) of the Vander Lugt type correlators.

In the second part of this Ph.D. Thesis we have introduced the description of color images, or hyper-spectral images, by means of three dimensional functions in which the third coordinate contains the color information. We have analyzed the color coordinate as a sample of the spectral distribution in each one of the points of the color image.

- ✧ The color Fourier transform, that is, the Fourier transform along the color axis has been defined. We have also defined the three dimensional Fourier transform for three dimensional functions that describe color images.
- ✧ We have shown that each one of the channels of the color Fourier transform represents an orthogonal projection onto one subspace of the corresponding color space. The subspaces corresponding to the different channels of the color Fourier spectrum are orthogonal each other.
- ✧ In particular, the projections corresponding to the channels of the color Fourier spectrum for the case of RGB color images have been determined. We have determined that the $m=0$ channel of the color Fourier spectrum contains the information of the intensity of the color, and that the chromaticity information is contained in the $m=1$ and $m=-1$ channels of the

color Fourier spectrum. The saturation is the ratio of the magnitude of the m=1 channel to the m=0 channel, and the hue is the argument of the m=1 channel.

- ✧ The main properties of the Fourier transform for the case of three dimensional functions that describe color images have been given. We have shown that the three dimensional spectrum of color images contains the interference between the objects in different channels of the image.

- ✧ The three dimensional correlation of three dimensional functions has been proposed as a valid technique for color pattern recognition. We have established the conditions for the three dimensional correlation to be useful for color pattern recognition. In particular we have demonstrated that, for recognition purposes, the three dimensional correlation function must be evaluated in the origin of the color axis because the color of the objects to recognize is not invariant for shifts along the color axis of the three dimensional functions that describe them.

- ✧ An interpretation of the filtering operations of the color Fourier spectrum as linear transformations of the color space have been given. We have provided a classification of the linear filtering operations. The high-pass and low-pass filters of the color Fourier spectrum have been interpreted, respectively, as dilatations and contractions of the color space along the axis normal to the 1/3-intensity plane. The effect of the high pass filter to the color Fourier spectrum involves an enhancement of the saturation of the colors in the image described by the filtered image, keeping unaltered the hue of the colors. The effect of the low-pass filter applied to the color Fourier spectrum of an image involves a reduction of the saturation of the colors in the reconstructed color image, keeping unaltered the hue of the colors. We have demonstrated that the only phase transformation of the color Fourier spectrum of an image is the application of a linear phase. The linear phase filtering involves a rotation of the color space about the normal to the 1/3-intensity plane. This rotation involves a modification of the hue of the colors of the filtered image, but the intensity and saturation are not altered.

✧ The interpretation for some non-linear operations such as the whitening of the Fourier spectrum has been given. We have demonstrated that the whitening of the color Fourier spectrum of a three dimensional function that describes a color image involves a normalization of the intensity of the colors and a maximization of the saturation of the colors of the image. We show that most of the colors resulting from the whitening of the color Fourier spectrum have negative components. This is interpreted as the amount of the corresponding primary color that must be added to the saturated color to obtain a non-saturated color that can be composed by addition of the remaining primary colors.

- ✧ The color-wise correlation of an image has been defined as the correlation of the three dimensional function that describes the image along the color axis, considering the addition of all the possible cyclic translations of the image along the color axis.

- ✧ The interpretation of the classic matched filter for color-wise correlation is given. We show that the color-wise correlation, evaluated at the origin of the color axis gives the scalar product between the vectors that point to the colors in the color space. Therefore the color-wise autocorrelation is maximum for the target color in comparison to the cross-correlations of the target color with any other color with equal or lower color energy.

- ✧ The phase only filter has been interpreted. We have shown that the color wise correlation using phase only filter represents a change between different orthogonal bases of the color space. In addition, because the whitening of the color Fourier spectrum is equivalent to a normalization of the intensity and the saturation of the colors of the image, we have provided an alternative path to perform the color wise correlation using this filter.

- ✧ The interpretation for the pure phase color-wise correlation is given. We have shown that in this case only the hue of the colors is taken into account for the recognition, and therefore the colors are classified by their hue.

- ✧ We have also considered whitening operations on the three dimensional Fourier transform of color images, and its implications on color pattern recognition. When the three dimensional Fourier spectrum of an image is whitened, the filtered image presents the typical edge enhancement of the colors, and the colors are also normalized (but the saturation is not exactly maximized). In this case the three dimensional autocorrelation is a sharp peak in the origin, and null elsewhere. This indicates both that the channels are decorrelated each other, and that the channels are also spatially decorrelated.

✧ The discrimination capability for three dimensional correlation involving different whitening operations for objects with similar shape and different color distribution has been compared. The whitening of the scene color Fourier spectrum is also proposed because it can be performed in the direct domain by means of normalizing the intensity and the saturation of the colors of the images.

In the third part of the Thesis, we have proposed a technique to encode the three dimensional functions that describe color images in two dimensional functions. The technique allows us to obtain the three dimensional Fourier transform and the three dimensional correlation.

✧ The proof that the proposed encoding can be used to obtain the three dimensional Fourier spectrum of the encoded image has been given. We have shown that the obtained Fourier transform corresponds to a non-orthogonal sample of the three dimensional Fourier spectrum of the three dimensional image.

- ✧ An interpretation of the encoding in terms of shifted carriers has been provided. This allows us to determine the sampling requirements for the encoded function, that leads to the orthogonal sampling of the three dimensional Fourier spectrum.

- ✧ We have also proposed a variant of the encoding technique in which one of the spatial coordinates is encoded on the color coordinate. We have also demonstrated that in this case the channels of the Fourier spectrum of the three dimensional image are interlaced.

- ✧ The proof that also the three dimensional correlation can be obtained by means of two dimensional operations by the proposed encoding technique has been given. We demonstrate that the $n=0$ channel is encoded exactly. In addition, for the other channels the error is very small if the values of two consecutive pixels are not very different.

- ✧ The implementation in the optical correlator of the proposed encoding technique has been performed. The bandwidth limitations of the optical system and the alignment requirements have been taken into account. Aside from the alignment procedure for the optical correlator, we have developed a Moiré technique to control the scale of the correlation plane with the camera CCD array, which is necessary for the proposed encoding.

- We have implemented three variants of the encoding technique: considering full bandwidth color encoding, half bandwidth color encoding and spatial encoding. The three dimensional correlation for color pattern recognition has been performed in the optical correlator using the three variants. We have obtained excellent results for both the three dimensional phase only filter and the color spectrum whitened scene, using a three dimensional phase only filter.

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