A Proposal for Applying Artificial Intelligence to Measure Ocular Refractive Errors

Antonio Valerio Netto
University of São Paulo, Institute of Mathematics and Computer Science,
São Carlos - SP, Brazil, 13560-241
aneto@icmc.usp.br

and

Maria Cristina F. de Oliveira
University of São Paulo, Institute of Mathematics and Computer Science,
São Carlos - SP, Brazil, 13560-241
cristina@icmc.usp.br

Abstract

In this work we describe the architecture of a functional system capable of processing Hartmann-Shack (H-S) images of the human eye and analyzing them to automatically diagnose and measure the presence of refractive errors in the eye under exam. Image analysis relies on connectionist Artificial Intelligence techniques such as Neural Nets, Fuzzy Logic and Classifier Combination. The major goal is to develop a new technology to measure ocular refractive errors (astigmatism, hypermetropia and myopia) that uses methods different from those adopted in patented systems. In general terms we are interested in investigating approaches for solving current difficulties related to interpreting and diagnosing these and other ocular problems by analyzing images obtained with this acquisition technique.

Keywords: Artificial Intelligence, Neural Networks, Fuzzy Logic, Image Processing, Hartmann-Shack or Shack-Hartmann, Ocular Refractive Errors, Principal Component Analysis.

1 Introduction

The goal of this work is to provide the basis of a novel technology for diagnosing and measuring eye aberrations that relies on image processing and analysis to enable the construction of an alternative equipment. Image processing techniques apply transformations to scanned or digitally acquired images with different goals, such as to improve image quality or to identify and extract relevant characteristics. A generic image acquisition and processing system consists of a card for image acquisition/digitization, a memory for storing images and a processor with a set of tools for displaying and manipulating the contents of the memory according to the application goals. A process of image analysis typically seeks to obtain information on the components of a scene from its visual representations [5].

We investigate the application of artificial neural networks [6] [12] and non-deterministic techniques such as fuzzy or neuro-fuzzy logic coupled with classifier combination to analyze images of the ocular globe in order to detect the presence of and measure refractive errors. There is a considerable amount of research describing successful applications of neural nets to extract information from images [1] [11] [21], and we believe this approach can provide the accuracy and efficiency required in this particular application domain. A system is under development, and is described here, in which images obtained by a technique known as Hartman-Shack sensor are processed to improve quality, remove noise, perform image registration and extract features that will be then input to a neural net architecture for classification into the existing types of refractive errors.

This approach opens up multiple possibilities for research on innovative devices for analyzing eye functionality. The possibility of identifying and analyzing eye characteristics from images of the ocular globe allows not only to diagnose refraction errors, but also to obtain additional information on the health of the eye. In the future, we may expect to obtain a complete mapping of the human eye from single acquisition equipment.

This paper is organized as follows: in section 2 the refractive errors to be handled by the system under development are described. In section 3 the principles of the image acquisition technique are introduced. In section 4 the overall architecture of the system is presented and its component modules are described. Final remarks on the current state of the project and its expected contributions are in section 5.

2 Ocular Refractive Errors

A condition in which the eye exhibits a difficulty in focusing the image on the retina is generically named as ametropia, or refraction error. Reduced vision, eye discomfort and occasionally headaches are major symptoms caused by refractive errors that may be usually eliminated by contact lenses or glasses that compensate for them. There are three major types of refractive errors, namely myopia, hypermetropia and astigmatism [2] [20].

In a somewhat simplistic analogy, the eye can be compared to a camera that transmits and focuses the light through its lenses by an opening of variable diameter, a diaphragm responsible for controlling the amount of light that enters and impresses the film. In this comparison, the eye lenses are the cornea and the crystalline, the iris and the pupil represent the diaphragm, and the film is the retina. Through refraction the eye focuses the incoming light in the retina: the cornea and the crystalline are the lenses responsible for refracting the light rays directing them towards the retina. The retina captures the image thus formed and transmits it to the brain via the optical nerve. Refractive errors appear when some alteration in the eye shape prevents a correct refraction of the incoming light.

Myopia is a disturbance in image focusing that causes the image to be formed before the retina, and prevents one from seeing distant objects clearly [4] [13]. It results from an increased curvature of the cornea or crystalline and can be corrected by divergent spherical lenses [2]. A myope eye is longer than a normal one and consequently light must travel a larger distance. Rather than focusing at the retina, as expected, focusing occurs before it, producing a blurred image of an object depending on its distance from the eye.

In hypermetropia there is also a difficulty in image focusing, but as opposite to myopia, focusing occurs behind the retina, thus preventing a clear focalization of near objects. It results from a smaller curvature of the cornea or crystalline lenses, and can be corrected by convergent spherical lenses [2]. Hypermetropia is quite common in children and may disappear as the eyes grow. Sometimes it occurs associated with strabismus (cross-eye), because the eye muscles must contract to see near objects properly [3]. Several surgical techniques are available for hypermetropia correction, such as Radio Frequency, PRK (PhotoRefractive Keratoplasty), LASIK (Laser-Assisted in SItu Keratomileusis) or ICL (Implant Contact Lens) [14].

Astigmatism is a condition that results from the eye cornea or crystalline having different curvatures in both directions, comparable to the different curvatures of an egg or an American football. This causes different focusing depths that distort both far and near vision. Most occurrences of astigmatism are congenital and do not change along an individual's lifetime. It can happen in conjunction with shortsightedness (myopia) or hypermetropia, and may be corrected by cylindrical lenses [2]. Surgery may be an alternative to glasses and contact lenses in some cases. Suitable techniques are radial keratomy, PRK, LASIK, radio frequency and implanted contact lenses [14].

3 Image Acquisition Technique

The human eye is a 'natural' optical system that acquires images: light rays enter the eye and form an image of an observed object in the retina. A major challenge for this project was to identify an appropriate form of acquiring functional information from the eye. As it is not a human-constructed optical system, it is particularly difficult to access the eye's optical images in conditions suitable for "measuring" them. We came across the Hartmann-Shack (H-S) or Shack-Hartmann technique [9] [17] when searching for approaches capable of providing functional information on the human eye suitable for input into an image analysis system. This technique, according to the opinion of specialists in Optometry [22], provides the principles for the construction of more effective anomaly meters (aberrometers) [22]. Its principles are outlined in the following.

If the eye is observing a sufficiently distant light point, such as a star, one may assume the incoming light rays are parallel when they enter the eye and are refracted to form a perfect point image of the object on the retina. In other words, if the source point is sufficiently distant it may be assumed that it emits light waves in a single direction, and the rays entering the eye take, essentially, the form of a plane wave. Taking the light rays simply as lines and assuming they are plane waves one may consider that the light wave front reaches the eye perpendicularly to it, which is equivalent to state that light rays are parallel. Inside the eye the waves change into circular waves and are later focused into a point in the retina [15].

One may consider the inverse process, what happens when light from a point on the retinal image is reflected back out of the eye. For a perfect eye, the emerging wavefront will be a plane wave and the rays will be parallel to each other. However, if the eye has some kind of anomaly the emerging wavefront will be distorted away from the perfect shape of a plane wave. Naturally, the reflected light will be very dim, but anyone who has ever had their flash photographs ruined by a red spot covering the normally black pupil of their subject's eye will appreciate that it is possible to capture photographically the light reflected back out of the eye with a bright enough flash. A system apparatus that can capture this reflected wavefront in order to support the measurement of eye anomalies is now described [17].

A point light source is created in the retina and the wave front of the eye's emerging light is analyzed by an array of fine lenses. This micro-lenslet array divides the wave front into several individual beams, each one focused in a CCD (Charge-Coupled Device) sensor. In a perfect eye the reflected plane wave will be perfectly focused into a grid of image points. An image will be generated containing all the points coming from the array of lenses, and the spacing amongst such points will be the same as the spacing between lenses in the lenslet. For a perfect plane wave the direction of light propagation is the same for all light rays, but in an anomalous wave the direction of light propagation varies within the wave front. Consequently, this system can be used to determine the shape of the light wave front propagation by analyzing the location of the points registered by the CCD sensor [16]. The light rays reflected by an imperfect eye are not parallel, and therefore they will focus the point images inordinately when reaching the micro-lenslet array. For an exact analysis of the location of each point in this disordered group of points one may calculate the slope of the anomalous wave front relative to the group of lenses, thus determining the type of anomaly.

The shape of the anomalous wave front, known as wave front aberration function, is the fundamental measure to evaluate the optical quality of the eye. This function is in the core of an optical theory that allows one to compute the image formed in the retina by some object, and then to evaluate the quality of this image and the eye performance in accomplishing visual tasks. However, to apply this optical theory it is necessary to analyze the wave front immediately after it passes through the pupil. Additional information on this system and its operational principles may be found in [7] [9] [10] [15] [16] [17].

The H-S acquisition system is calibrated with an artificial normal eye globe, which allows a later comparison with images of human eyes under exam to verify the presence of anomalies. This calibration, or optical-mechanic adjustment required by the equipment suffers small alterations due to external factors, possibly introducing errors in the measurement of refractive aberrations.

4 Measurement System

We propose a system architecture for measuring refractive errors [18] with three components operating in three stages, as depicted in Figure 1. The first component would be the image acquisition system, which we assume is available elsewhere. Our work is restricted to the development of the image processing and analysis components of the system.

As we do not have a local acquisition system available, a database with nearly 700 images obtained from the School of Optometry of the Indiana University, acquired from their H-S equipment is being used to develop and test the image analysis components. Such apparatus, called "Aberrometer" [17], is illustrated in Figure 2, which also display typical images. Each image in the database is associated with metadata informing the refractive errors (if present) and their corresponding measures. Each image has a data group, called a “Power Vector”, which characterizes its measurements, as illustrated in Figure 3.

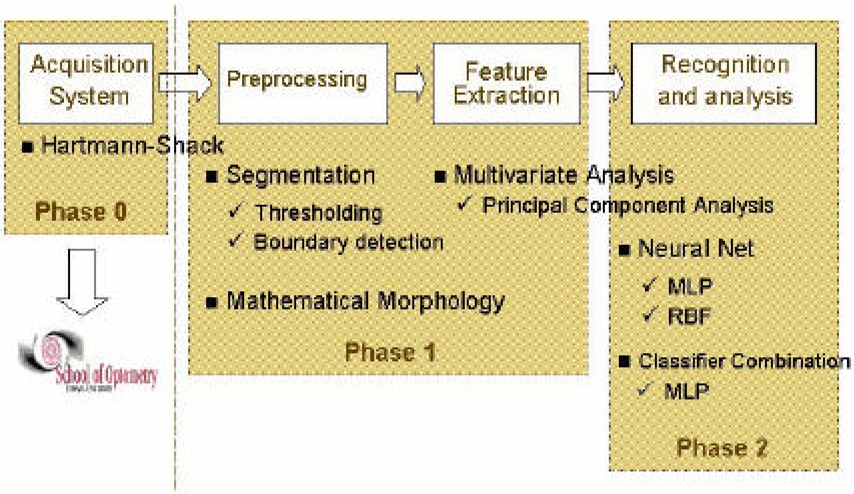

Figure 1 – Overall architecture of the system for measuring refractive errors.

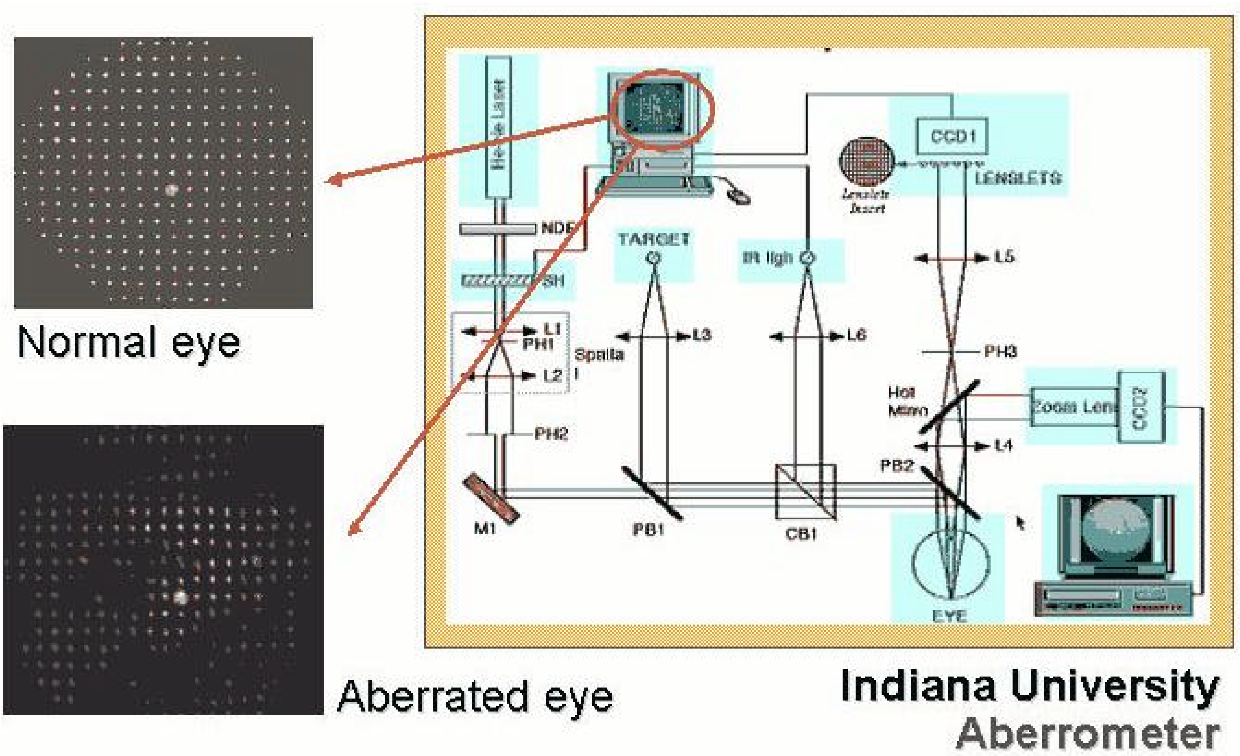

Figure 2 – Overview of the acquisition hardware (right); images produced by a normal (top left) and by an anomalous eyes (bottom left).

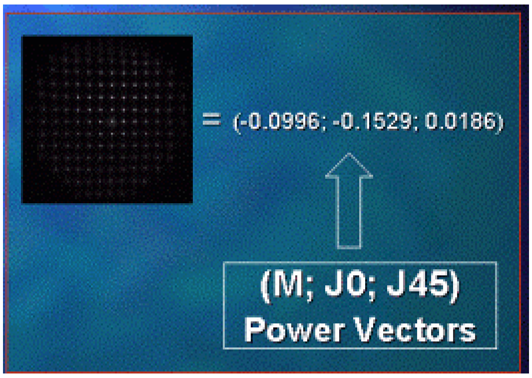

Figure 3 – Correspondence of an image with its refractive error measurement data.

A "Power Vector" takes the form (M; J0; J45), whose values for a positive cylinder are given by Equations 1.1 to 1.3, where S is the Spherical lenses (for myopia or hypermetropia), C is the Cylindrical lenses (for astigmatism), and A is the axis of astigmatism.

$$M = S + \frac{C}{2} \quad \text{(eq. 1.1)}$$

$$J0 = -\frac{C}{2}\cos 2(A + 90^0) \quad \text{(eq. 1.2)}$$

$$J45 = -\frac{C}{2}\,\text{sen}\, 2(A + 90^0) \quad \text{(eq. 1.3)}$$

The above representation is a description of spherical-cylindrical lenses from a Fourier analysis viewpoint, and it is convenient for handling problems involving combination of lenses, comparison amongst different lenses and verification of the statistical distribution of refractive errors [22]. The "Power Vector" provides an abstraction of the information (measures) relative to myopia, hypermetropia, astigmatism and astigmatism axis embedded in the image. As such, it supplies information to train and validate the neural nets that will perform image analysis. From the Power Vector refractive error measurements for positive cylinder may be obtained from equations 2.1 to 2.3.

$$S = M - \sqrt{J0^2 + J45^2} \quad \text{(eq. 2.1)}$$

$$C = 2\sqrt{J0^2 + J45^2} \quad \text{(eq. 2.2)}$$

$$A = \frac{1}{2}\tan^{-1}\left(\frac{J45}{J0}\right) + 90^0 \quad \text{(eq. 2.3)}$$

The first component of the image processing sub-system applies pre-processing operations and feature extraction to the H-S images, preparing them for the later recognition and analysis stage. Image pre-processing is essential for the feature extraction process to be successful, as the presence of noisy images and images with badly defined or blurred dots has been observed in the database. Moreover, image alignment and registration is necessary because not all the images were taken over the same interest area relative to a unique axis. Such characteristics are illustrated in the three images depicted in Figure 4.

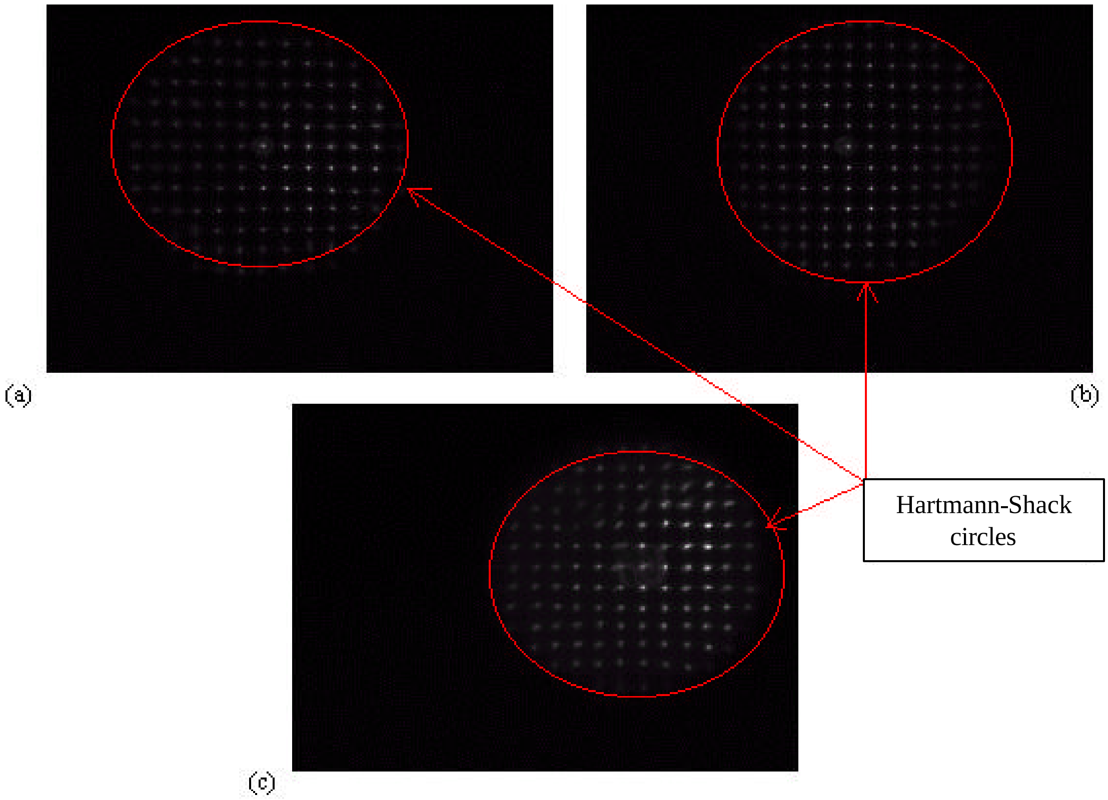

Figure 4 – H-S images from the database of the School of Optometry, Indiana University. Interest area (Hartman-Shack circle) is highlighted.

The goal of the pre-processing component is to generate a modified image database where the interest areas (the so-called "Hartmann-Shack circles") are identified and aligned relative to a unique central axis. The preprocessing techniques to be applied include noise elimination without border displacement and histogram analysis [23] or, alternatively, mathematical morphology to identify the most extreme dots making up the HS circle. Figure 5 illustrates the application of a noise elimination process developed for "cleaning" the images.

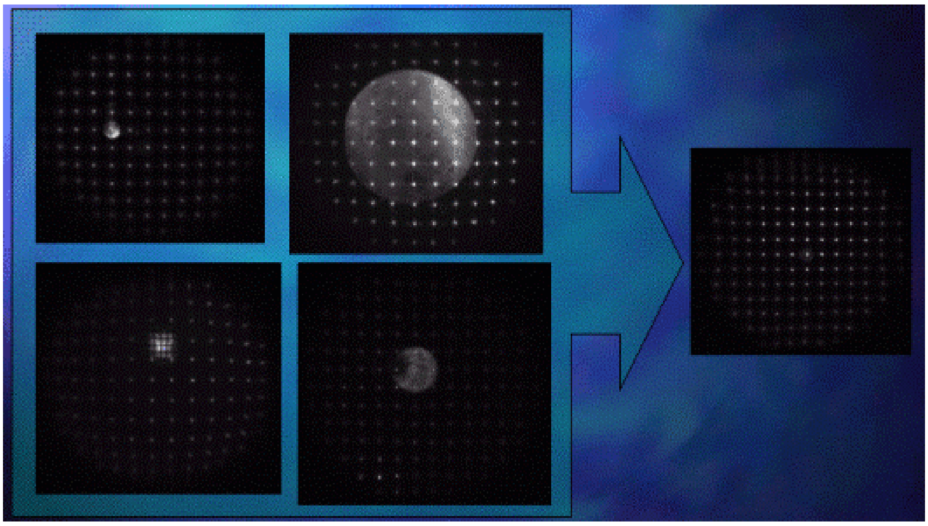

Figure 5 – Noisy Hartmann-Shack image that must be cleaned in the pre-processing stage [18].

Application of histogram analysis techniques enhances the contrast of "dots" relative to the image background, thus allowing the identification of the most extreme dots. This is to allow computation of the radius and center of the

Hartmann-Shack circle. With this information it is possible to align and to clip all database images based on the largest pupil diameter present.

Still in this architectural component feature extraction is performed by applying the PCA (Principal Component Analysis) method, which does the data reduction. This is necessary to reduce the number of inputs for the third system component, the neural net architecture that analyses the images. The classic PCA reduces image dimensions ensuring that relevant information is not lost, as illustrated in Figure 6. Resulting data from the feature extraction process will be fed into the analysis sub-system, a neural net architecture possibly coupled with a combination of classifiers. The pre-processing and feature extraction module is being implemented in the C programming language on a LINUX platform, using the public domain software *VDKBuilder* for development.

Development of the third component of the architecture, responsible for outputting a diagnosis on the existing refractive errors based on an analysis of the extracted image features, requires the definition of a suitable neural architecture and a training stage using the available image database. After training, such architecture should take as input the feature vector of a newly acquired image and analyze it in order to detect the presence of refractive errors in the imaged eye, also outputting a measure of such errors. This component is under development.

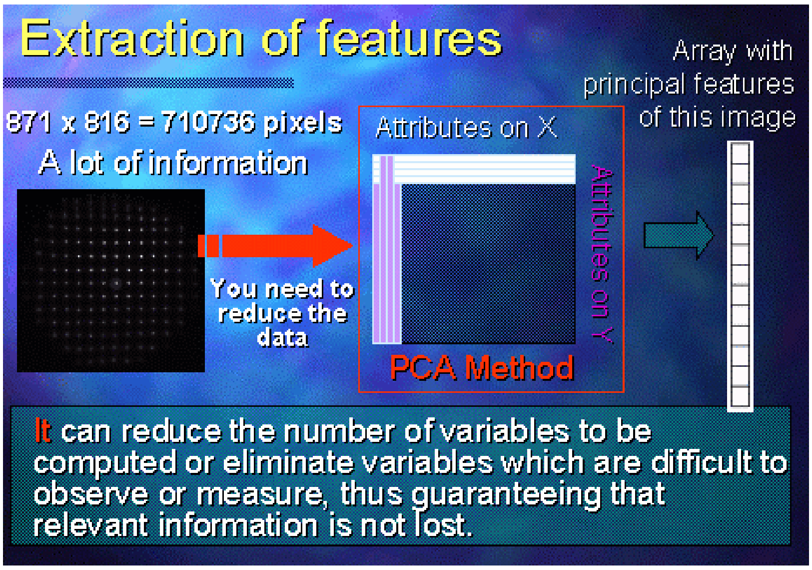

Figure 6 – Image feature extraction using the PCA method [18].

Several neural net architectures are being investigated, initially using SNNS (the Stuttgart Neural Network Simulator) [24], a flexible neural net simulation environment that runs in UNIX platforms and is freely distributed over the Internet. We shall be initially testing both the MLP (Multi-layer Perceptron) and RBF (Radial Basis Function) organizations. Based on the results obtained, we may extend the investigation to other architectural models. SNNS is convenient because it allows us to explore the great number of possible parameter combinations (number of layers, weights, learning algorithm, etc.) and variations and test a considerable number of possibilities that would otherwise demand a high processing time. Its use will simplify the identification of the net architecture that better adapts to the input data, as not all possibilities will have to be implemented. The neural architectures investigated will undergo a supervised training process, using a sub-set of the images available in the database, in order to learn to identify the "Power Vector" of each image.

An overview of the steps executed by the whole pre-processing and analysis sub-system is presented in Figure 7. Two approaches shall be verified to input the "Power Vector" data in the training step, namely, providing the three vector elements (M, J0, J45) simultaneously, or using a different neural net to analyze each component. Depending on the classification performance exhibited by the nets investigated, we shall consider a classifier combination based in another neural net (MLP). Alternatively, one may consider the possibility of creating a new approach to solve the problem [25].

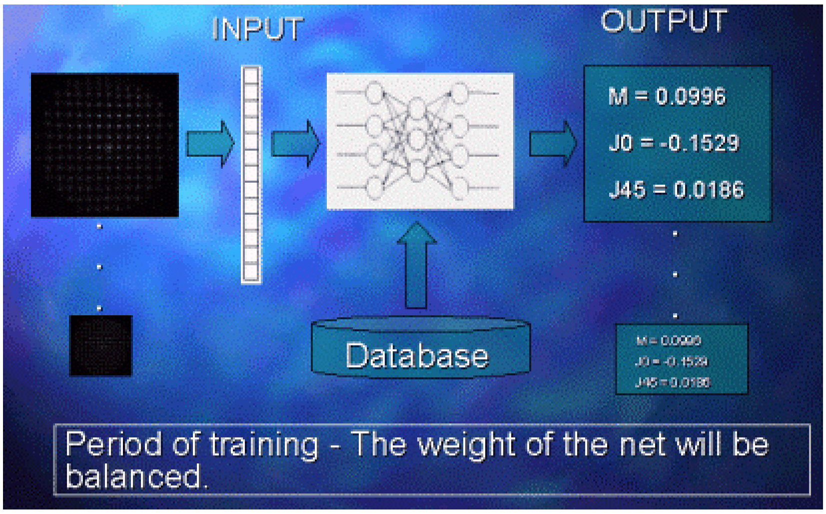

Figure 7 – Overview of the whole data analysis system [18].

5 Final Remarks

In this work we describe the overall architecture of a system capable of automatically analyzing images from the human eye acquired with the H-S technique and output a measure of refractive errors in the eye. The huge progress in research on practical applications of neural nets to a range of domains over the last years certifies their precision and efficiency to analyze and recognize external input data. This motivated the investigation on their application as the basis of a system capable of recognizing H-S images corresponding to anomalous eyes, as well as detecting the type of anomaly and quantifying its magnitude.

The purpose of using neural networks for image analysis is to provide the system with adaptability and robustness, that is, it should be capable of providing error measures by 'understanding' the data, rather than by direct image comparison, as it was previously accomplished. Such an 'intelligent' software may provide a starting point for solving current difficulties related to optimization and calibration of the acquisition system and for interpreting and diagnosing other ocular problems from images acquired with the same technique, such as the one known as " Tear Film Breakup" [8]. As such, our approach opens up various possibilities in terms of academic research on ocular globe recognition. The possibility of recognizing and analyzing characteristics of the ocular globe allows not only the diagnosis of the refraction errors mentioned in section 2, but also to obtain additional information on the health of the ocular globe. To the best of our knowledge, it is the first time such techniques are being applied to H-S images in Optometry. We believe the project provides a good opportunity for a closer approximation between the areas of Computer Science and Optometry. Furthermore, a practical contribution of this approach is to provide the basis for a new technology to measure ocular refraction errors based on image analysis techniques.

Acknowledgements

The authors are grateful to **Professor Larry Thibos** from the School of Optometry, Indiana University - USA, for his helpful support and for supplying the H-S image database. They also acknowledge the support of FAPESP, the State of São Paulo Research Funding Agency, Grant 00/04779-2, and CNPq, The Brazilian Research Funding Agency, Grant 521931/97-5.

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