UNIVERSITY "POLITEHNICA" BUCHAREST

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PhD THESIS SUMMARY

CONTRIBUTIONS TO THE STUDY OF OPTICAL SYSTEMS IN OPTOELECTRONIC DEVICES WITH APPLICATIONS

Author: **Eng. Gheorghe Bostan**

DOCTORAL COMMISSION

Președinte	**Prof. Dr. Ing. Ion MARGHESCU**	de la	Universitatea Politehnica din București
Conducător de doctorat	**Prof. Dr. Ing. Paul STERIAN**	de la	Universitatea Politehnica din București
Referent	**Prof. Dr. Fiz. Doina Mănăilă MAXIMEAN**	de la	Universitatea Politehnica din București
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Referent	**C.S.I. Dr. Fiz. Mihai Lucian PASCU**	de la	Institutul Național pentru Fizica Laserilor, Plasmei si Radiațiilor, Măgurele-București

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1. Introduction.

Presentation of the doctoral thesis field. A multitude of phenomena can be manifested when recording the image of the object and its particularities, for example: reflection, refraction, absorption, dispersion, auto emission, induced emission (fluorescence, luminescence). These effects depend on the optical properties of the material of the object of interest, the structure of its surface (the degree of roughness, its dielectric coatings). In principle a distinction is made between the surface effects, caused by the discontinuity of the properties, and the effects that occur in the volume of the object.

The term "machine vision" is used to characterize a system that monitors an area of interest or controls an industrial process. The computerized vision like the eye as a biological organ plays an active role, it explores the environment, it rotates, it catches the focus of interest, it adjusts the angle of observation. It is obvious the complexity of the procedures for the quantitative visualization that depend on the particularities of the optical scheme, the specificity of the problems to be solved.

The current state of development regarding optoelectronic video inspection systems. The field of high definition video cameras for surface inspection is in continuous development. Modern cameras are equipped with motorized lenses that provide a ~ x30 zoom which means microscopic magnification with the mention that it is performed from a much greater working distance (~ 250 mm) compared to that of a microscope which is only a few mm, this allows the examination of various objects of different sizes. "Video inspection camera" are required by specialists from the various fields in which the optical examination and quality control are used: boards with electronic PCB components, high precision micromechanical devices, security applications, etc. Also measuring non-contact dimensions, documenting and archiving a large number of images. Modular design for adaptation to different scientific, military, security and industrial applications.

Purpose of the doctoral thesis. In order to obtain quality images, a multispectral illumination system is required, as it has been called in the specialized literature. The purpose of the doctoral thesis is to develop the methods and techniques of multispectral illumination and image acquisition using the digital camera with CMOS optical sensor. These researches require more knowledge about the subassemblies of the component of such a system, image capture, with regard to resolution and clarity. images, it involves the recovery of the characteristics, of the object, the image of which is to be processed in order to highlight the following properties: the reflective characteristics of the foreground and background elements, for an optimal number of recordings. This paper tries to provide an answer to the colorimetric and spectral accuracy that can be achieved, combining the knowledge about the possibilities of the calibration system of the recording parameters by using the methods of characterization of the recording equipment.

A series of requirements are imposed on the digital camera. It must be controlled by the computer. To have the zoom function to take the object of interest in the viewfinder and bring it to the foreground on the monitor. The resolution of the camera must ensure the visualization of the elements of interest, of micrometric dimensions.

The content of the doctoral thesis. The research included in the doctoral thesis had the following objectives:

– to study and to model the spectral illumination in order to design more efficient devices taking into account the new technologies;

– development of methods for modeling the functioning of LED lighting devices needed to improve the acquirement of images when examining protected documents;

– optimization of the technology for testing the optical system resolution;

– modeling the optical transmission processes using the diffractive optics methods that were presented during the research,

to these are added several complementary objectives:

– to present the current state of research in the field regarding computer vision;

– methods of optimization and realization of spectral illumination with RGB LED systems;

– the realization of subassemblies from new components appeared on the market, especially light sources of high efficiency and reliability;

– improvement the methods of self-testing the optical resolution by characterizing the optical transfer function.

The doctoral thesis is structured on 8 chapters, written in 126 pages and includes 88 figures, 4 tables, 62 mathematical relations, 54 graphs and 151 bibliographic references.

Chapter 1, introductory, includes: – presentation of the field of doctoral thesis; the current stage of the development of optoelectronic video inspection systems: - the purpose of the doctoral thesis and the content of the doctoral thesis; The research included in the doctoral thesis had the following objectives: - to study and to model the spectral illumination in order to design more efficient devices taking into account the new technologies; - development of methods for modeling the functionality of LED lighting devices; - optimization of the technology for testing the optical subsystem resolution; - modeling the optical transmission processes, the modulation transfer function, using the diffractive optical methods.

Chapter 2, entitled **Principles and methods of modeling optoelectronic imaging control systems** describes the technological chain of image production that begins with the radiometric description of the scene to be captured by the digital camera; the methods of modeling the process of recording the image, the origin of the colors in materials and the materials for protective elements used in the protected documents including the optical methods of examination taking into account a complex of physico-chemical measures, by methods of optical and electron microscopy, chromatography , ultraviolet, visible and infrared spectrophotometry; Interaction of the surface with light: it is analyzed based on the radiative transfer equations to calculate the energy flows transferred from one flux to another or absorbed by the environment. Also in this chapter are analyzed the optical methods of document verification and the consideration of the spectral illumination coordinates.

Chapter 3, entitled **Principles and methods of testing optical resolution for optoelectronic systems with adaptive optics,** describes the requirements for the optical system, testing methods, the spread functions and the slanted edge method used to describe them.

Chapter 4, entitled **Theoretical and experimental contributions to the development of optoelectronic systems for image control**, shows methods and techniques for illuminating the region of interest, color manipulation, for better contrast, also the angle of incidence and the degree of diffusion of the surface are key factors for obtaining smooth images. The lighting conditions are very important when inspecting the elements of the region of interest in the scene. The chapter deals with: the use of optical band filters in combination with digital filters in the spectral lighting system; the method of spectral illumination by replacing incandescent light sources with LED sources; modeling the intensity profile of the luminous flux emitted by the coaxial illumination source for homogenization of the illumination of the region of interest (flux collimation, LEDs, field diaphragms; method of illuminating the ROI region of interest of the surface examined using RGB LEDs; optimized optical scheme elimination of specular reflections when examining laminated documents with protective plastic; in the optical scheme of the document verifier device; development of the modularization method of the optical spectral illumination scheme with the help of high intensity optical fibers; the method of colorimetric estimation of the object of interest with the help of a video camera by calibrating the Bayer filter transfer functions. Also presented are: colorimetric measurements made by integrating into the optical scheme of the hyperspectral camera for surface examination; using the features of the hyperspectral camera to analyze the signature stamp inks in the protected documents thread. amplification of the chromatic contrast by numerical simulations of superposition of the illuminant spectra, surface reflection and the sensitivity spectrum of the digital camera. At the end of the chapter, a summary of the obtained results is made and the conclusions of the studies carried out are presented.

Chapter 5 entitled **Contributions to the development of methods for testing optical resolution for optoelectronic systems with adaptive optics** examine in the following chapters the testing of optical resolution for a system with adaptive optics, addressing the following problems: the method of estimating the correlation between the optimal digital resolution of the CMOS sensor, and the lens optical resolution; limited by the phenomenon of diffraction with the requirements of the optical scheme; results regarding the development of the inclined edge method; computerized simulations of the slanted edge with different degrees of light diffusion to optimise the calculation algorithm and minimize errors. Finally, the conclusions of these studies are presented.

Chapter 6, entitled **Final Conclusions. Original contributions. Trends and Perspectives**, describes the results of the research carried out.

Chapter 7, entitled **List of published works**, presents the list of the author's publications that served as the research base for the present doctoral thesis..

Chapter 8, **Bibliography**. The doctoral thesis ends with a selective bibliographic list consisting of 153 titles of articles from specialized journals, national and international scientific conferences.

2. Principles and methods of modeling the optoelectronic systems of image control

2.1 Methods of numerical modeling the imaging system. In machine view the scene represents a multidimensional matrix that describes the spectral radiance [1] (photons / sec / nm / m2) for each pixel of the scene [2]. The scene emits or spreads light rays in all directions. The camera's optical system captures some of these divergent rays, so that they are gathered in the plane of the irradiating image in front of the optical sensor. For calculating the optical irradiance of the image, a number of factors must be taken into account. Firstly f-number, magnification, secondly the shading or weakening of the light when passing through the lens surfaces [3], (relative illumination), thirdly: the image blurring factor, the blur, may occur due to the limit of wavelength dependent diffraction, due to optical distortions, only part of the rays converge in the same focus; the described data define the camera equation, for the calculation of the image irradiance on the optical sensor. Fig. 2-1.

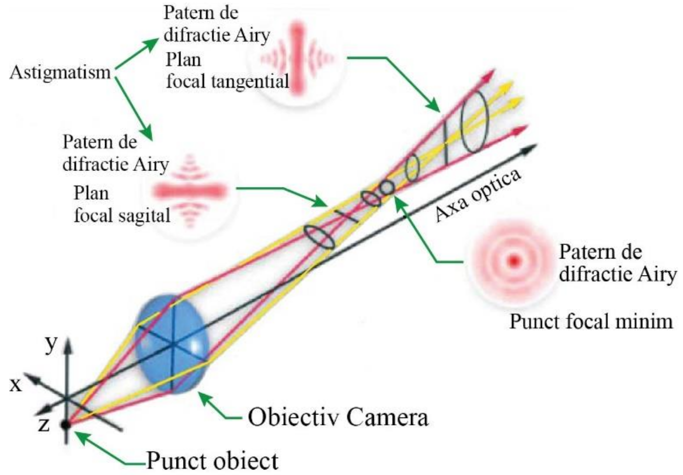

Fig. 2-1 Circle of least confusion, a focused beam of light at the point of best focus for the image [4]

The equation of the camera defined for the simplified model of the conversion of the radiant function of the scene L_{scene} in the irradiation (optical) field of the image on the sensor, is:

$I_{imagine}(x, y, \lambda) \cong \frac{\pi T(\lambda)}{4(f/\#)^2} L_{scena}\left(\frac{x}{m}, \frac{y}{m}, \lambda\right)$ (2.1); L_{scene} is the radiant function of the scene; f $\#$ is the effective f-number of the objective (focal length divided by the effective aperture); $T(\lambda)$ lens transmission; m is the magnification of the lenses; The coordinates (x, y) specify the position towards the center of the image [5]. The decrease of illumination with the removal of the main optical axis is called relative illumination or relative shading: $R(x, y, \lambda) = cos^4\theta \approx \left(\frac{d}{S}\right)^4$ (2.2); The term S is the height of the image field (distance from the optical axis) and d is the distance from the lens to the image plane.

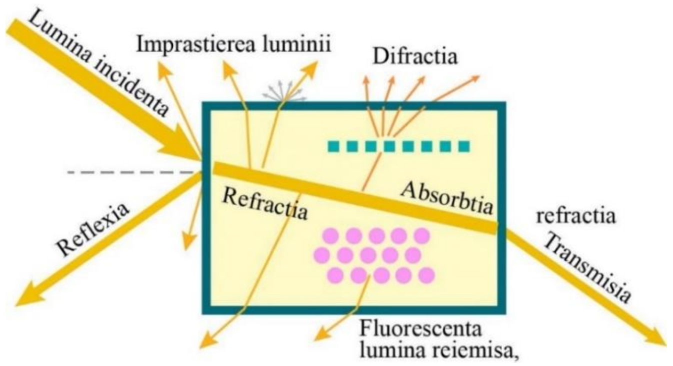

Fig. 2-2 Interaction of light with matter include such effect as reflection, refraction, diffraction, scattering, absorption, reemission as fluorescence, the effect of each of these processes varying with wavelength and give us different colors [6].

2.2 The origin of colors in materials. The spectral composition of light emitted by a light source when interacting with the surface of the solid body, is subject to various changes in the diffusion, reflection, refraction, diffraction, transmission, absorption process [7]; As a result, the objects under a single illumination reflect the light of different spectral compositions towards our visual system and produce the perception of colors Fig. 2-2. Color is a subjective notion of individual perception. In physics, all measuring devices operate at wavelengths.

2.3 Materials for security elements used in protected documents, optical examination methods. Modern documents contain a variety of materials intended for protection. Besides the cellulose fibers of which the paper is composed, there are included metallic threads, luminescent fibers in certain types of radiation, other chemical compounds that protect the document at the chemical composition of the material [8]; To study the component materials of the document substrate, a complex of physico-chemical measures, optical and electron microscopy, chromatography, ultraviolet, visible and infrared spectrophotometry is used [9].

2.4 Interaction of the surface with light. As the light penetrates deeper into the material, it is more scattered and the intensity of the directional flux is reduced while the intensity of the diffused flux is increased. Therefore a useful model for light propagation in an opaque material can be developed using only four streams: two directional flux (one forward and one back) and two diffuse flows (again one forward and one back) [10], which we call setup- or the arrangement for the 4-flow theory. Radiative transfer equations are established to calculate the energy flux transferred from one flux to another or absorbed by the environment fig 2-3.

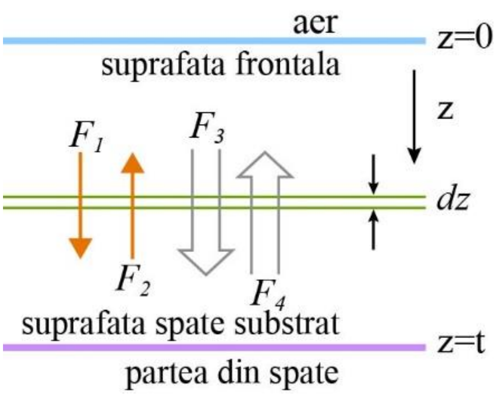

Fig. 2-3 The four-flux theory about light interaction with surface, there are two directional fluxes F1 and F2 and two diffuse fluxes, F3 and F4.

2.5 Optical methods of document verification. The methods of protection with graphical elements involve different shapes, textures, networks of lines of different sizes and combinations of arrangements [11], [12]. With the help of ultraviolet or infrared lighting, you can view graphic elements, invisible in ordinary viewing conditions. Means of protection may include microtext, luminescent fibers [13]- [14]. All the protection elements are visualized by optical methods with the use of specialized equipment. In order to certify the authenticity of the documents or the effective detection of the forgeries of the documents, optoelectronic devices, called video comparators are used.

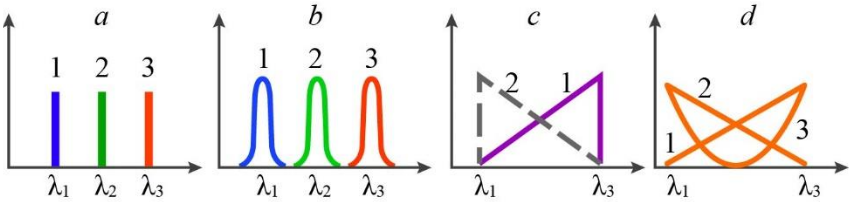

Fig. 2-4 Spectral sampling: a) spectral lines radiation, b) spectral band sampling, c) sampling the entire radiative flux and the average wavelengths, d) sampling the entire radiative flux, the average wavelengths and the wavelengths variant, [15].

2.6 The spectral illumination coordinates. Spectroscopic visualization is a powerful tool for highlighting the properties of the examined objects, because the optical constants of the materials, the reflection, the refractive index, the absorption, diffusion, luminescence coefficient, depend on the wavelength. Spectral lighting adds a new coordinate to the visualization, and the amount of data multiplies accordingly. Therefore, it is important to sample the spectrum with a minimum number needed, sufficient for optimal visualization [15], Fig. 2-4.

3. Principles and methods of optical resolution testing for optoelectronic systems with adaptive optics

3.1 Introduction. Compared to the video cameras used for the computerized view and in various fields of security assurance, there are imposed requirements for measuring the quality of the images. The method of calculating the modulation transfer function for an imaging system has developed with the emergence of increasingly efficient optical sensors for digital cameras [16], [17] .

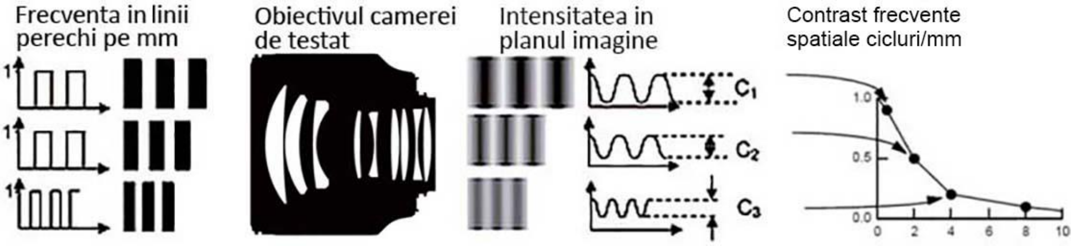

Fig. 3-1 The contrast transfer function [18] [19]- [20].

3.2 Optical transfer functions. (Spread functions). Optical transfer functions describe fundamental physical processes that manifest themselves in the field of imaging. If the inputs into a linear, stationary imaging system have a sinusoidal shape, then the outputs have a sinusoidal form, reduced in amplitude due to losses [21]. The modulation reduction for a particular frequency ω is known as the modulation transfer factor Fig. 3-1. The graph of the dependence of the modulation transfer factor on the frequency ω is also called the modulation transfer function.

Modeling the image formation process is a convolution operation (denoted by *), expressed in the distribution of the image irradiance $g(x, y)$, ec. (3.2), as a convolution between the function $f(x, y)$, of an ideal image and the response pulse $h(h, y)$: $g(x, y)=f(x, y)*h(x, y)$ (3.2);

3.3 The Slanted edge method. A slanted edge between white and black with sufficient contrast is recorded (photographed). The image of the edge is always more diffuse than that of the edge object due to loss of transfer through the optical system. An important feature of the method is the intelligent creation of the 1D profile of slanted edge (ESF edge spread function) through the projection on the x axis of the pixels located on parallel vertical lines, the y axis, the coordinate system rotates so that the y axis either parallel to the slanted edge, thus oversampling, with the 1/4 pixel step, which allows a good enough accuracy for calculating the ESF function, which is then derived to obtain the line spread function (Gaussian type function) [22]. The next step is the Fourier transform of the LSF function into a series of frequencies. The result is the MTF (modulation transfer function) which represents the ability of the system to record spatial frequencies, thus implicitly the quality of the examined optical system [23], [24].

4. Theoretical and experimental contributions to the development of imagistic control optoelectronic systems

4.1 **Using the optical band filters in combination with digital filters in the spectral lighting system. Optimization methods** It is known that in order to make a compact and ergonomic device, it is necessary to optimize the optical scheme. As a result of the experiments it was found that, in most cases when the incident light interacts with the examined surface, the reflection spectrum changes. After passing through the optical filter and interacting with the examined surface, the light from the source changes its reflection spectrum. The video cameras are calibrated from the Factory to see the colors correctly. In front of the CMOS optical sensor of the Camera the Bayer filter is placed and adjusted to interpret the colors fig. 4-1. Positioning an additional filter in front of the lens does nothing but duplicate the existing filter [25].

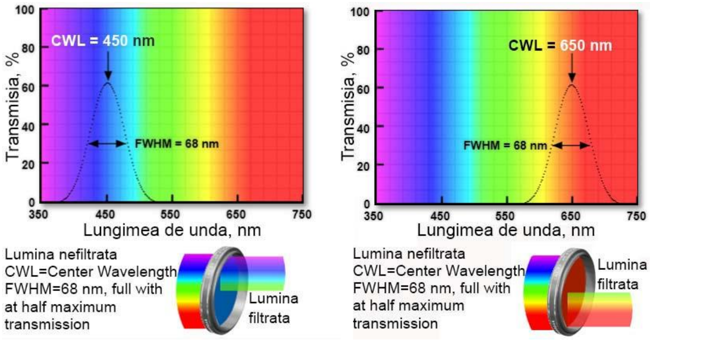

Fig. 4-1 The optical filter transmits only part of the incident light, it is characterized by the transmitted wavelength (or color), the bandwidth (FWHM), the transmission (%), as well as the high-pass, low-pass, narrow-band, interference filters. [25]

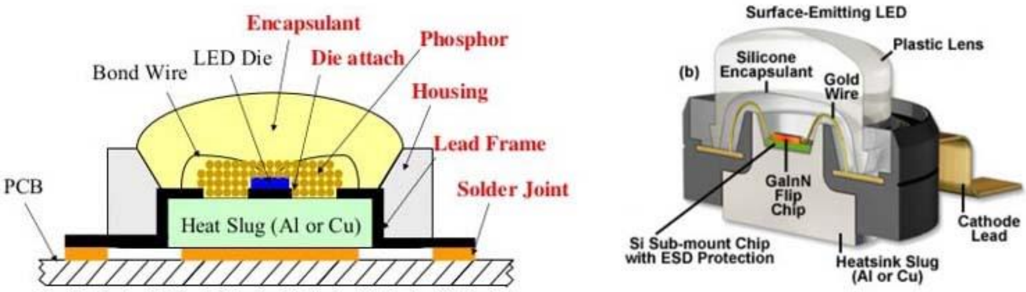

Fig. 4-2 The main components of an LED [28]

4.2 **The method of spectral illumination by replacing incandescent light sources with LED sources**. The selection of a suitable illumination method is essential in the applications of protected document control and also in microscopy. LEDs are more durable, do not require expensive power supplies. In addition, a wide range of LEDs with UV / VIS / NIR spectral emission are available, with various bandwidths Fig. 4-2. The white light emitting LEDs in the color temperature range from 2500K up to 6000K are a very good selection for illuminating the region of interest and recording quality images. An optical feature of LED sources is the directivity diagram; Advantages: 1) Long service life; 2) Efficiency 85% -90% compared to traditional lighting; 3) Extremely resistant to mechanical shocks; 4) Power supply from low voltage sources; 5) smaller divergence of the luminous flux due to the integrated optics; 6) Color temperature covers a wide range from hot light 2200-3200 to warm yellow light 3200-4500 and cold light 4500-7000 (white-blue); 7) Instant switch to lighting state without blinking [26], . [27].

4.3 Modeling the intensity profile of the luminous flux emitted by the coaxial illumination source for homogenizing illumination of the region of interest; (LEDs flux collimation, field diaphragms). When inspecting the various surfaces with the digital camera, as in microscopy, the homogenous illumination of region of interest is very important Fig. 4-3. By selecting appropriate lighting, the contrast can be significantly amplified and thereby improve the quality of the recorded image. Especially when it is required to visually compare image elements located at some distance within the region of interest. The role of homogenous lighting becomes particularly important [29]. Or for example when the digital color of the studied element is near the limit of the chromatic sensitivity of the digital camera. The resolution decreases not only with the spatial frequency of the black and white bars, but also with the change of the color of these control bars. For the homogenization, the methods used in microscopy have been developed. The use of the special optical diffuser, in combination with diaphragms with rectangular profile. helps to model the luminous flux profile [30].

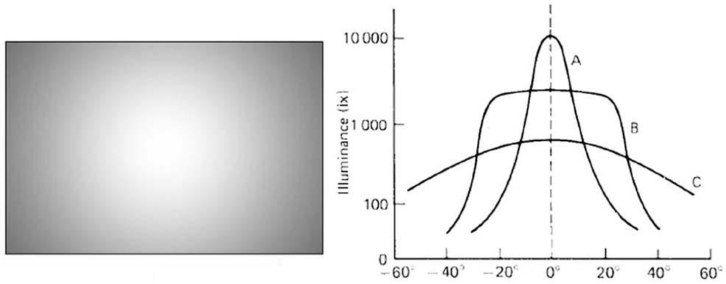

Fig. 4-3 Inhomogeneous illumination of the region of interest; measurements for adjusting the lighting intensity profile.

4.4 Method of illuminating the area of interest ROI of the surface examined using RGB LEDs. The use of LEDs in lighting technology has long attracted the attention of specialists for low energy consumption and low maintenance costs. To create white light with LEDs, there are two approaches: the separate use of 3 RGB LEDs, connected in an optoelectronic scheme of mixing three monochromatic radiations from each LED, mixing the monochromatic colors will result in color light, depending on the color the amount of colors component of the light generated by the 3 LEDs [31]. Another method is to use LEDs that emit shorter wavelengths from the visible, the blue light and convert it into white light with the help of fluorescent phosphorus coating fig. 4-4. The approach of mixing the colors by using of 3 LEDs offers a greater luminous efficiency, because the losses caused by the conversion to white light in the environment of the fluorescent phosphorus layer are avoided, Fig. 4-5. Moreover, color mixing LEDs provide flexibility in obtaining colors. Therefore, color mixing LEDs are the long-term preferred method for producing quality white light.

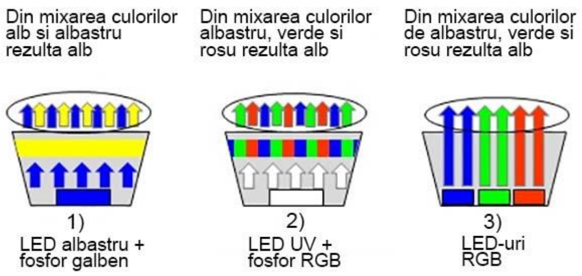

Fig. 4-4 Optical schemes of white color formation in LEDs

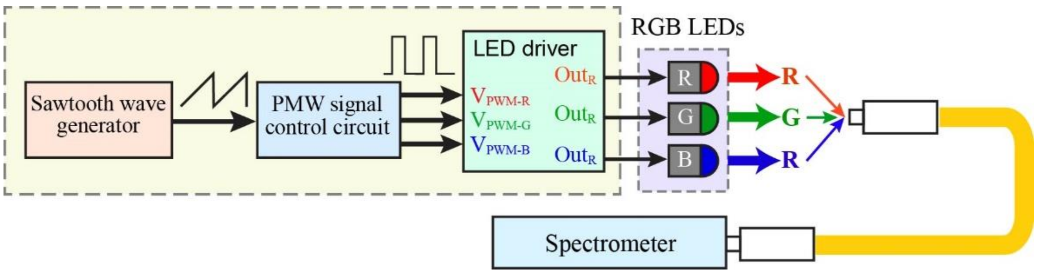

Fig. 4-5 Scheme of the white light forming device and color shades using RGB LEDs [32].

4.5 Optimized optical scheme for eliminating specular reflections when examining laminated documents with protective plastic; in the optical scheme of the document verifier. The way in which the material sample surface interacts with the light in a specific application of surface examination is related to many factors: texture or surface relief, degree of roughness, surface shape, topography, interaction geometry, reflectivity, chemical composition, color . The light reflected by certain surfaces under certain angles becomes polarized, resulting in mirror specular reflections (direct, non-diffuse, glints), fig. 4-6. Reducing the brightness to avoid glare and maximizing the quality of the recorded images is achieved by using polarization filters in front of the light source and in front of the camera lens. The camera's glints are explained by the fact that the sensor pixels have entered in saturation mode, [33], [34].

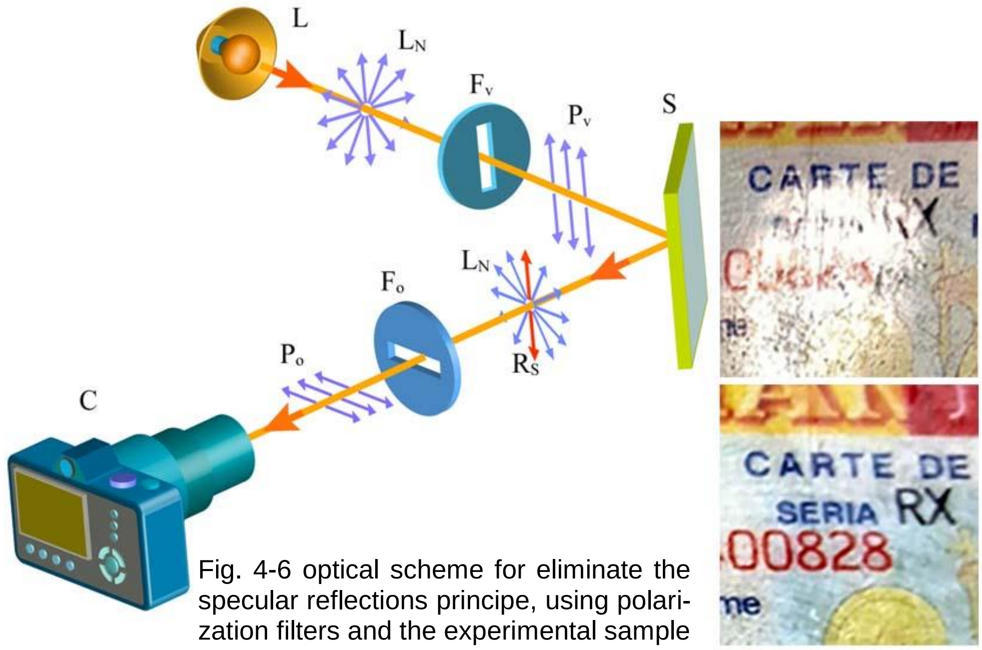

Fig. 4-6 optical scheme for eliminate the specular reflections principe, using polarization filters and the experimental sample

4.6 Modularization method of the optical spectral illumination scheme using high intensity optical fibers. Different types of lighting are used when viewing and examining objects of interest in the field of view of the rooms. Both the power supply of the bulb and the bulb, during operation releases a large amount of heat, depending on the electrical and optical power required for lighting. The need to increase the power arises when in front of the light source are placed bandpass optical filters that let only a small part of the light source to pass. A modern technical solution is the grouping of the components described in a distinct functional module, removing its outside the enclosure, which has been achieved. The modification can be done if we use high intensity optical fiber to bring light into the camera. The advantages are obvious, and it comes from engineering estimates, the positioning in an accessible place within the device. Modularity involves replacing the filter turret with another necessary filter turret.

Simple, fast installation. Simplified construction. Dispose of the electrical cables from the location intended for lighting [35].

4.7 The colorimetric method of estimation the object of interest using the video camera by calibrating the transfer functions of the Bayer filters. One way to use the camera as a colorimeter is to find the correspondence function between RGB values and CIELAB values. For polygraphic printed surfaces, this approach has been shown to produce the best results, when calibration and measurements are performed on the same printed samples with the same combinations of polygraphic materials used. As we know the measurements with the spectrocolorimeter are made in point, due to the specificity of the device If we have to measure in several points the process is time consuming. As the machine accuracy is higher the more expensive. In general, spectrometers are expensive devices. Using the camera gives us the opportunity to perform estimated, fast measurements for a large number of points at relatively low costs.. Do not forget that for this type of adaptations there are not used the cheapest digital cameras. Initially an assessment is made about the possibility of using the technical capabilities of the digital camera for colorimetric measurements. Camera adaptation can be made by direct estimation, spectral estimation, which means direct estimation from RGB numerical vectors. (number values of the triad of colors red, green, blue, with which all other colors are formed). Once the color difference calculation formulas are widely used. The color difference between the reference and reproduced colors was calculated from the estimated spectra using the digital camera, [36], [37], 120]. The way to calculate such a spectral estimate is to approximate the sensitivity functions (or transfer spectra) of the RGB filters in the Camera and use this to estimate the spectral distributions. In front of the camera is placed an adjustable monochrome light source, which can emit different wavelengths of narrow enough bandwidth and which can be recorded using the camera's sensor. Of course the F-number camera settings, focal length, source brightness will be registered. The numerical response vectors recorded are those that characterize the transfer functions of the room filters.

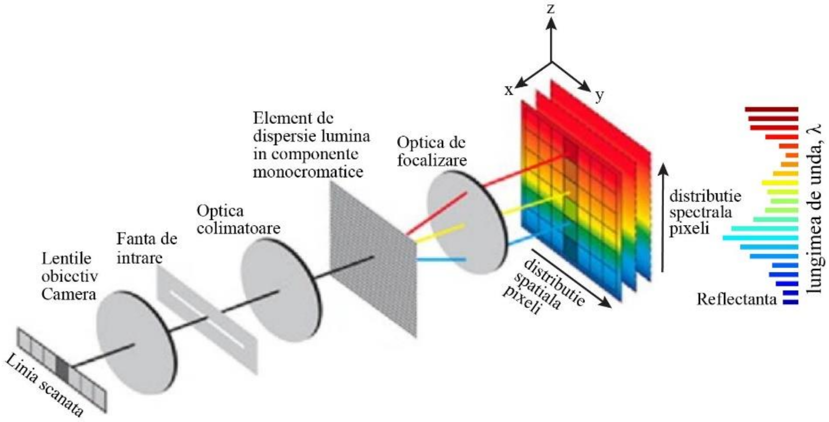

Fig. 4-7 Hyperspectral camera. Optical scheme Each pixel image contains data about the visible spectrum 400-730 nm with step 10 nm; 330 nm / 10 nm = 33 intervals. The pixel color is given by 33 color planes.

4.8 Colorimetric measurements by integration into the optical scheme of the hyperspectral camera for surface examination. Spectral analysis allows for the identification of materials, it is like a fingerprint of material identification. Verifying the authenticity of security color elements in protected documents is an important operation that allows the detection of forgeries. In the hyperspectral camera each image pixel contains data about the entire visible spectrum from 400 nm to 700 nm, or even more, depending on the destination of the camera, it may contain data from UV, NIR, FIR, spectra, [38] [39]. The hyperspectral image is characterized by 3 dimensions, x-axis resolution, y-axis resolution and 3rd, spectral dimension. The data on the hyperspectral image form a data cube, a three-dimensional, cubic matrix fig. 4-7. Each slice of the cube is called a channel, or a spectral band. For example, the sensitive optical sensor in the 400-700 nm range can record 128 spectral bands, (700-400) /128=2.3 nm, with the 2.3 nm step the amplitude of the reflected radiation is recorded, which is a sufficiently good resolution. For specific applications the advantage of using hyperspectral camera is obvious. thus some components disappear from the optical scheme of the device for the criminological expertise of the protected documents, so the turrets with optical filters together with the electric drive motors, electronic control and power circuits.

The camera contains within it the optical filtering and the wavelength selection system. The camera contains within it the optical filtering system and the wavelength selection. Thus, the main optical scheme is simplified with the number of functional elements already integrated in the camera [40].

4.9 Using the hyperspectral camera features for analyzing stamp inks, signature inks, in protected documents. The hyperspectral camera is a useful tool for non-destructive examination of protected documents, containing pigments in printing inks, inks in handwriting, in stamps etc. It is known, handwriting is done with certain inks, some of which include identification elements. That is why, they have a well-defined color and therefore a unique spectrum that identifies them. The use of hyperspectral images gives us an obvious advantage, more precise, less errors high speed of work. An important property of the images is the fact that it allows to more precisely perform the segmentation of the image elements according to various criteria, first of all by identifying the color shades to highlight the barely visible characteristic. The obtained results showed, the system's qualities can be enhanced by a high-performance lighting system. Hyperspectral image can help us to restore barely legible text from old documents, for example by recording images every 15 nm from 400 nm to 700 nm and then by analyzing these images we can select the image with the best contrast [41], [42].

4.10 Chromatic contrast amplification by numerical simulations of superposition of the illuminant spectra, surface reflection and digital camera sensitivity spectrum. Forming the image of an object is a physical process, the light emitted by illumination source towards the object of interest, is reflected by it towards the camera lens system, behind which is the image plane. Thus the color of an element of the scene is obtained by integrating the spectral power distribution of the illuminant, the spectral reflectance of the object and the spectral sensitivity of the CMOS optical sensor of the camera. Since the creation of an arbitrary lighting spectrum is not realistic, it is essential to compose the most suitable lighting available [43], [44]. Therefore it is useful to find the most suitable lighting using linear combinations of the available illuminants. If we have controlled light sources, whose emission spectra l_1 , l_2 , ... l_N are given, the problem of finding the best linear combination of light sources can be formulated, [45], [46]; The proposed method is useful both for optoelectronic devices for surface analysis of the protected documents as well as in the medicine for endoscopic visualization etc.

4.11 Results. Illumination, sample positioning and optical capture are the basic hardware components required for image acquisition. The image captured by the camera is formed mainly by the light reflected by the objects of the scene of interest. The colors of the image may vary depending on the lighting, when the camera is targeting a particular scene.

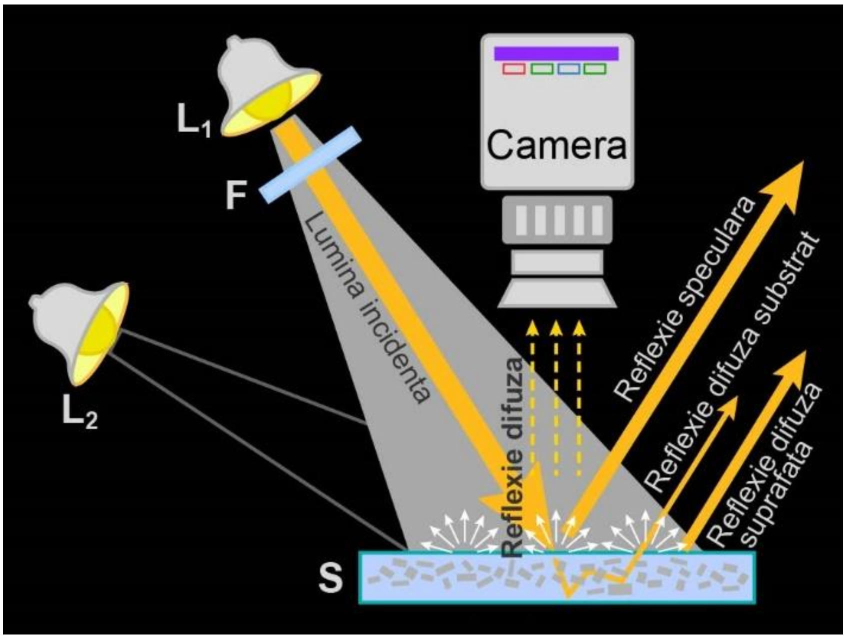

Fig. 4-8 The main components of a surface inspection imaging system: light source, L_1, L_2, digital camera with optical sensor, reflecting surface, S (scene), optical filter F.

Typical arrangement for illumination is made from tungsten-type light sources halogen or LED, white, for the most part, the color temperature or specific, involving the operations of adjustment of white balance. Determining the proper light source, light intensity, angle of incidence and diffusion are key factors in obtaining fine images. The lighting conditions are very important when inspecting the elements of the region of interest of the scene fig. 4-8. Efficient lighting technological solutions, by adding collimation lenses in front of light sources, are important for optimizing the optical image recording scheme Fig. 4-9, Fig. 4-10.

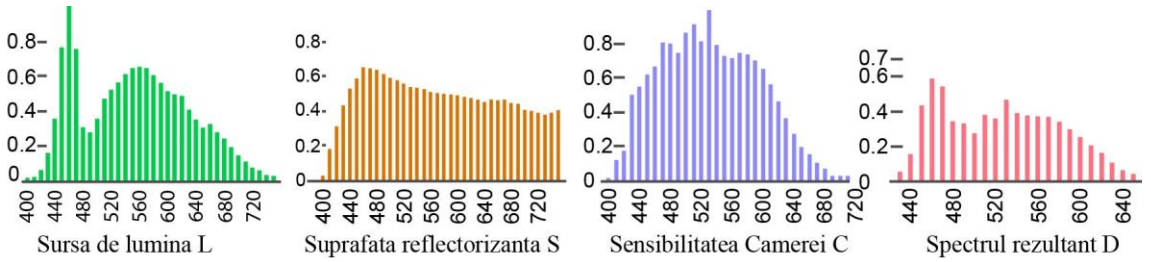

Fig. 4-9 Spectral interaction of light, light source L, reflective surface S, digital camera sensitivity C, resulting spectrum D

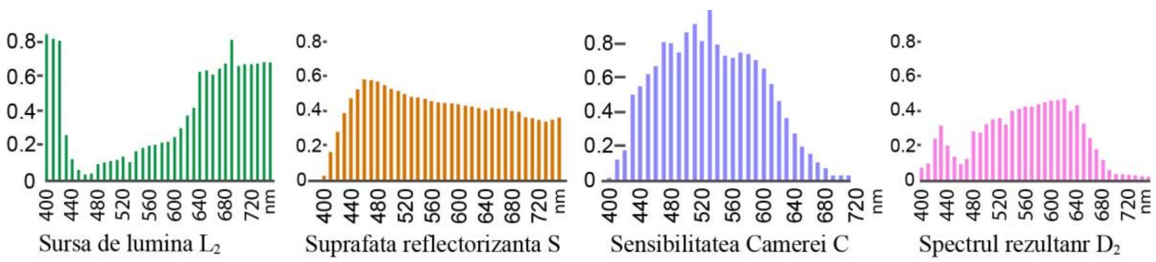

Fig. 4-10 The light source emission spectra modification induces the modification of resulting spectrum see Fig. 4-9 and implicitly the image quality recorded by digital camera.

4.12 Conclusions. From the test images recorded, the type of illumination, and the illumination spectrum, is very important, in order to obtain a clearer image, particularly when the foreground elements have shades close to those of the background Fig. 4-11. The color resolution of the device has been improved..

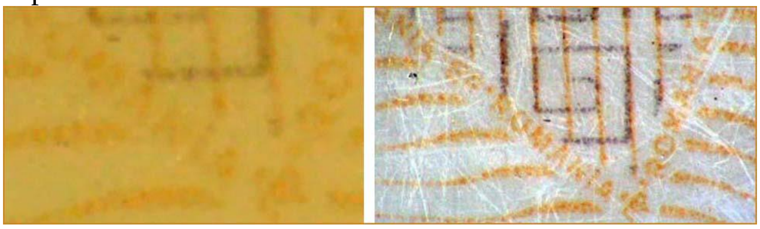

Fig. 4-11 During video inspection of the document surface the role of the illuminator and its spectral composition is very important to get a high quality image

The method of controlling the emission and reflection spectrum also contributed to the improvement of the device's functions.

5. Contributions to the development of methods for testing optical resolution for optoelectronic systems with adaptive optics

5.1 The method of estimating the correlation between the optimum digital resolution of the CMOS sensor and the optical resolution of the lens system limited by diffraction, with the requirements of the optical scheme. Image resolution is an important characteristics, especially in microtext inspection applications of micrometric dimensions of approximately 70-100 μm. The contribution refers to the development of methods for analyzing the optical characteristics of the digital camera lens system; From the multitude of digital cameras existing on the market, where for each camera there are several lens systems, and where a lens system fits several cameras, it is a problem to be solved in finding an optimal digital camera-performance lens system. which maximizes the overall performance of the camera. In order to have higher resolution, the image sensor must have more pixels, more pixels on the same area of the sensor means smaller pixels but smaller pixel means fewer photons captured and in such cases there are problems that the designer hits. The pixels become smaller until they reach the barrier of the fundamental limit of physics, the pixel cannot be much smaller than the wavelength [21], [47]. When selecting the camera for the visualization system, the calculation of the minimum focal point was taken into account [48]. Size which have to match the sensor pixel size . If the focal point is greater than 2-3 times the pixel size then the optical resolution does not match the digital resolution given by the optical sensor, or if the lens does not provide the required optical resolution.

5.2 Results regarding the development of the slanted edge method. The camera resolution with CMOS sensor can be verified with the help of special control charts with black and white bars of various spatial frequencies, or using the slant-edge method. The second method involves a series of calculations for constructing the graph of the MTF function that displays the contrast as function of frequency, (at high frequencies the contrast decreases) cy / px, cy / mm, lp / mm. The advantage of the slant edge method is that, when we do not have a special resolution control target available, or we do not have the possibility to disassemble the camera from the device to test it on the measuring stand in the laboratory, we can perform resolution measurements using the slant-edge method, [49]. The image of the slanted edge appears on the CMOS sensor, as an edge inclined by light from low intensity (dark area) to high intensity, bright area Fig. 5-1; The edge spread function (ESF) is divided into the pixel intensity profile when it goes from dark to bright. The LSF (line spread function) is calculated from the ESF function by deriving it. The result is a Gaussian profile function. The LSF function decomposes into the Fourier series by DFT operation (Discrete Fourier Transform), based on the obtained results Fig. 5-2, the graph of the modulation transfer function (MTF) is plotted, which represent the transmission of spatial frequencies by the optical system.

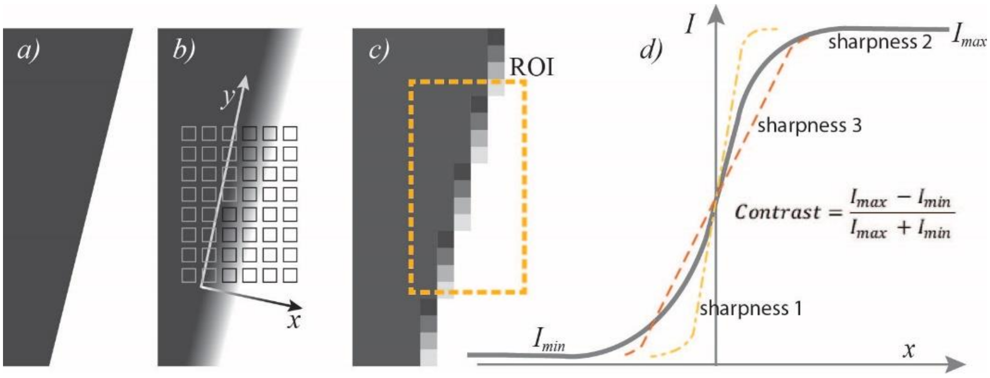

Fig. 5-1 (a)-target object, slant edge; (b)-the image of a slanted-edge object, projected onto the CMOS optical sensor pixel array; (c)-example of slant edge sampling by the optical sensor array, pixel size: 0.00428 mm (4.28 μm); (d)-intensity profile of slant edge.

5.3 Computer simulation on recording the slanted edge image between black and white with different contrast slope, for developing the optical resolution calculus method and minimizing errors. Several models of slanted edges very close in shape to the real ones were simulated on the computer. The study of the light intensity gradient on the optical sensor, formed by the image of the slanted edge allows us a faster estimation of the image quality, from which experimental data for the calculation of the ESF function are extracted, the calculation algorithms are verified. The slanted edge method is useful because it offers the possibility to calculate the transfer function of the lens system [50]. The image of slanted edge will be more diffused due to the optical losses caused by the lens system, which include the diffraction phenomenon at the entrance aperture, but also other optical distortions caused by the lens imperfection, as well as the optical centering of the lens groups. The slanted edge computer simulation is useful for verifying and improvement of measurement technique, noise reduction.

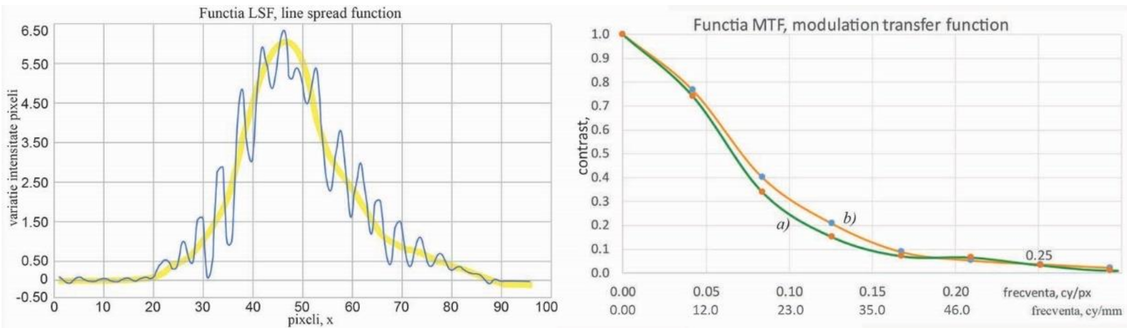

Fig. 5-2 Line spread function LSF, calculated by deriving the edge spread function, ESF, Fig. 5-1d. Modulation transfer functions, MTF calculated by discrete Fourier transform method of LSF, on the horizontal axis the values are in cy/px or cy/mm; cycle means the period of the spatial signal. Curve a) - original signal without noise filtering, b) - signal with noise filtering (on the right graph).

5.4 Conclusions. In the presented experiment, we investigated the relationship between the modulation transfer function and the gradient width model, using de slanted edge method. The computerized simulation of the luminous intensity gradient model on the optical sensor, is a way of verifying the calculation method, the possible errors in the calculation method, verifying the sampling procedure, perfecting the model. The graphs of the built MTF function, show us, the narrower gradient of the slanted edge or the LSF function, the more MTF function curve has a slope lower relative to the horizontal line, the system transmits high spatial frequencies better, resolution is better, and conversely, the wider the edge gradient, the slope of the MTF curve is steeper; high frequency transmission decreases to zero, system resolution decreases

6. Final conclusions. Original contributions. Trends and Perspectives

6.1 Obtained results. In the present work were realized the development and improvement of the methods of spectral illumination and recording of images in video inspection systems with applications in the examination of protected documents; Methods of controlling optical resolution were studied by developing the slanted edge method. The results of these researches have been successfully applied in the upgrade of the control equipment with applications in video inspection of surfaces, have been published in specialized articles. The study focused on the application of optical methods to study materials contained in protected documents, of the original security elements integrated into the paper, the plastic layers from which a document or another is made.

6.2 Original contributions. In the present work, several original contributions have been developed, especially of the optical components and subassemblies, which must satisfy the increasingly advanced requirements dictated by the user as well as the competition, among which energy efficiency, weight, performance, maintenance, etc. Most of the contributions have been described in the list of clean papers in Chapter 7 and include the following.

1) Use of optical band filters in combination with digital filters in the spectral lighting system. Optimization methods; The chromatic contrast was increased at the first stage in correlation with the use of digital filters, at the second stage for color balance adjustment; chap. 7, [1];

2 The method of spectral illumination by replacing incandescent light sources with LED sources; The lighting scheme has been optimized using LEDs. The advantage of which is small dimensions, more light, less heat; chap. 7, [2];

3) Modeling the intensity profile of the light flux emitted by the coaxial illumination source for homogenizing the illumination region (light flux collimation, LEDs, field diaphragms), when a smartphone camera takes a picture of crumpled white paper, the camera will see much more shadows than the human eye, which tends to subconsciously replace the shadows with white; since the digital camera does not have a subconscious (but may have), uniform lighting algorithms have been developed to homogeneously illuminate the region of interest by modeling the gaussian luminous intensity profile, for recording high quality images chap. 4, p.4.5; chap. 7, [2];

4) Method of illuminating the region of interest ROI of the surface examined using RGB LEDs; The illumination with a specific color can be archived by the use of optical band filters or by the use of 3 RGB LEDs, by controlling the amount of light emitted by each LED you can get a variety of colors that can successfully replace the classic optical filters. New technical solutions have been developed, applied in devices for video inspecting documents and other surfaces. chap. 4, p.4.6;

5) Optimized optical scheme to eliminate bright highlights reflections when examining laminated documents with protective plastic; When we examine a surface that contains bright elements that can blind the eyes, we automatically change the position to get rid of bright light, in a specialized device, software and hardware solutions are needed to eliminate the glare on the camera. General solution are not always suitable for a particular application. Technical solution have been developed to eliminate the bright light spot on the digital camera; chap. 4, p.4.7; cap. 7, [2];

6) Development of the method of the optical scheme modularization of spectral lighting using high intensity optical fiber; High intensity optical fibers allow light to be brought into the region of interest, and modularize the optical scheme. Original solution were implemented for placing lighting sources in a separate module; chap. 4, p.4.8;

7) The method of colorimetric estimation of the object of interest using the inspection video camera by calibrating the transfer functions of the Bayer filters; In some specific applications, the camera can be used for colorimetric estimations, after a preliminary calibration. Color test targets were recorded. RGB values were registered and a conversion table was defined. When registering a color, the values of the rgb pixels had the correspondence in the calibration table the respective color values are displayed. Interpolation algorithms were applied when the color was close to one of the colors in the calibration table; chap. 4, p.4.9;

8) Colorimetric measurements using hyperspectral camera integrated into the optical scheme for surface examination. The hyperspectral camera is an alternative method to the one described on p. 7. Contains a factory calibrated micro spectrometer. The method is useful for use in specific video inspection applications and colorimetric measurements, chap. 4, p.4.10;

9) Using the hyperspectral camera features for analyzing stamp inks, signature inks, in protected documents. It has been proposed as the method for colorimetric measurements of inks and pigments in printing inks using the Hyperspectral Camera; chap. 4, p.4.11; cap. 7, [1];

10) Amplification of the chromatic contrast by numerical simulations of superposition of the illuminant spectra, surface reflection and the sensitivity spectrum of the digital camera. The method of numerical modeling was developed of the spectral interaction between the illuminant, the examination surface and camera sensitivity, in order to perfect the imaging system; chap. 4, p.4.12; cap. 7, [2];

11) Development of the slanted edge method for testing optical resolution for an optoelectronic system with adaptive optics and MTF function calculation, to improve the characteristics of video inspection system; chap. 5, p.5.1; cap. 7, [3];

12) Calculation of the MTF function for optical resolution testing for an optoelectronic system with adaptive optics by the slanted edge method; calculation algorithms optimization. Statistical method used to increase calculation accuracy and causes that influence it.; chap. 5, p.5.1; chap. 7, [3];

13) Computerized simulations of slanted edge of different widths to improve the calculation algorithm and minimize errors. The slanted edge is a line of the shadow passing from dark to light (bright) whose width is influenced by the diffraction phenomenon on the lens aperture as well as by other factors, the ones presented are a contribution to the development of the calculation method; chap. 5, p.5.1; chap. 7, [3], [5];

14) The method of estimating the correlation between the optimum digital resolution of the CMOS sensor and the optical resolution of the lens system limited by diffraction, with the requirements of the optical scheme, has been developed; chap. 5, p.5.4;[3],[5].

6.3 Further development perspectives. Machine vision is a field of research that encompasses a broad spectrum of interdisciplinary activities. Such as, physics, semiconductor physics, photonics, optoelectronics, incandescent arc light source technology, light emitting diodes, photo-vide-o camera technology, hyperspectral cameras, software algorithms for video data processing, image processing science and prototype recognition, computer science, the science of vision, spectrophotoradiometry, colorimetry, artificial intelligence, nanotechnologies and micromechanics etc. Obviously, the development of devices with visual function of an eye involves knowledge and activities that are quite complex.

The results obtained in the framework of the doctoral thesis can be used to increase the performance of the optoelectronic video inspection equipment, to extend the functionality, to increase the reliability and the operating time by using the spectral illumination technologies.

The research performed in the thesis framework can be use by research laboratories, specialized institutions in video surveillance and security, control of protected documents, video inspection of electronic boards, etc.

7. Published articles

7.1 Articles published in scientific journals.

[1]. T. Necsoiu, G. Bostan, P. Sterian, M. Berteanu, *Materials for security elements used in protected documents, optical examination methods*. A review. Annals of the Academy of Romanian Scientists, Series on Science and Technology of Information ISSN 2066-8562 Volume 10, Number 1/2017

[2]. T.Necsoiu, G. Bostan, P.Sterian, *Spectrophotometric method for optimizing image capture conditions for inspecting protected documents*, Journal of optoelectronics and advanced materials, Vol. 19, No. 11 - 12, November – December 2017, p. 729 - 737

[3]. G. Bostan, P.Sterian, T.Necsoiu, A. P. Bobei, C. D. Sarafoleanu The slanted-edge method application in testing the optical resolution of a vision system, *Journal of optoelectronics and advanced materials*, Vol. 21, No. 1-2, January-February 2019, p. 22-34

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[5]. T.Necsoiu, G. Bostan, P.Sterian, Results on the optical trannsfer function of the optical systems evaluation by slanted edge method, Journal of Physics: conf. series 1297, 2019

7.2 Scientific reports and conferences.

1. T.Necsoiu, G. Bostan, P.Sterian, *Materiale pentru elemente de protectie utilizate in documentele protejate, metode optice de examinare*, Comunicare științifică The fifth edition of the International Colloquium "Physics of Materials" - PM-5; organized by the University POLITEHNICA of Bucharest, and the Academy of Romanian Scientists, between November 10-11, 2016

2. T.Necsoiu, G. Bostan, P.Sterian, *Metoda spectrofotometrica de optimizare a conditiilor de captare a imaginilor cu ajutorul camerei video pentru inspectarea documentelor protejate*, Comunicare științifică, Sesiunea Științifică de Toamnă a Academiei Oamenilor de Știință din România, Timișoara 12 -14 octombrie 2017

3. T.Necsoiu, G. Bostan, P.Sterian, *Testarea rezoluţiei optice a unui sistem imagistic robotizat prin metoda "slant edge", comunicare stiintific*., la Conferinta științifică de primăvară 2018 a Academiei Oamenilor de Știință din România, 30 martie 2018, București.

4. T.Necsoiu, G. Bostan, P.Sterian, *Modelarea gradientului de lumina in calculul functiei de transefr a modulatiei pentru un sistem optic prin metoda marginii inclinate*, comunicare stiintifica la Simpozionul anual al doctoranzilor SD-ETTI-B editia I, 9 iulie 2018, Bucuresti

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