Hyperspectral imaging: the colorimetric high ground

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ABSTRACT

Color is the human sensory perception triggered by a portion of the electromagnetic spectrum commonly called light. Mechanisms for capturing and reproducing these perceptions can trace their origins to four events. First, Newton’s deduction that “white light” was a mixture of rays able to induce the sensation of color in a human. Some 140 years later Young offered a physiological explanation for color perception, photosensitive receptors in the eye, which came to be known as the trichromatic theory. About 55 years later Maxwell applied Young’s theory to photography, demonstrating the three primary process that even now underpins commercial methods of capturing and reproducing color. And finally, In 1931, an international scientific standards organization, the International Illumination Commission (CIE), offered a precise, reproducible system for measuring and specifying color. However, CIE31was never integrated into the generally accepted procedure for reproducing color. The goal of this paper is to demonstrate, via discussion of technical issues and disclosure of a practical image capture device, that the CIE31method and related improvements, collectively described as hyperspectral imaging, can be integrated into the general process of color reproduction. The author maintains hyperspectral imaging is the path to virtually all future color reproduction techniques.

Keywords: hyperspectral, multispectral, spectrophotometric, colorimetric, color, imaging, color scanning, remote sensing

1. INTRODUCTION

Color perception is one of the few truly intuitive capabilities possessed by a typical human. Unlike learning to speak or operating the graphical user interface of a computer, it just happens. However, communicating the perception to another person is not intuitive and requires, at a minimum, training, or, as the communication becomes more sophisticated, measurement.

By the time we are in grammar school, most of us have been trained to recognize the visual sensations, or stimulus, triggered by the color of a lawn as green and those triggered by the sky as blue. The average person does not need or require knowledge of color beyond this psychological level and can spend an entire lifetime substituting adjectives for empirical measurement. But, for those fascinated by Newton’s insight into the properties of light and curious about the three hundred plus years of science it inspired, adjectives will not do. Reproducible colorimetric measurement becomes the only acceptable form of communication.

At the top of the colorimetric measurement food chain, above the well-trained eye, above the trichromatic colorimeter, above the abridged spectrophotometer and above multispectral technology, one finds the hyperspectral device. Until now, this technology has been limited to select military, medical and scientific applications. This document will introduce a new application, graphical scanning.

The term hyperspectral will be defined and compared to multispectral. Mechanical aspects of hyperspectral measurement, including creating and measuring bandpasses, will be discussed, and a review of currently available systems, applications and standards will be presented. Finally, a practical device, a hyperspectral imager for graphical applications, will be introduced.

2. DEFINITIONS

Before a picture can be imaged and its color communicated, the psychological perception of color triggered by the image

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must be measured. These psychological perceptions are triggered by a physical process, the interaction of a source of illumination, an observer and a specimen.[1] As illumination is, at its most basic level, electromagnetic radiation, imaging is a process controlled by the physics of Spectroscopy and the associated phenomena of refraction, the deflection of light rays, diffraction, the modification of light rays by passing them through or reflecting them off a ruled surface, and dispersion, the use of refraction or diffraction to separate light rays into component bands perceived as color. More specifically, Visible Light, the portion of the electromagnetic spectrum that stimulates the psychophysical sensations associated with color perception, is a continuous segment of the EM spectrum found between the wavelengths of 360 nm and 830 nm. By utilizing Spectrophotometry, the physics of visible light, and the related scientific disciplines of Photometry, the measurement of the intensity of light and Colorimetry, the numerical specification of the spectral radiant power distribution of a visual stimulus' color, reproducible measurements are achieved. For the purposes of this document, the continuous segment of wavelengths found between 380 nm and 780 nm will be defined as human-visible color, that portion of the EM spectrum associated with the psychological perceptions, from shorter to longer, violet, indigo, blue, green, yellow, orange and red.

As the EM spectrum is continuous, for practical purposes wavelength is often calibrated in discrete, nm (nanometer) denominated units, with groups or multiple wavelengths described as bandwidth. When the bandpass of the bandwidth is relatively wide, between 10 and 20 or more nanometers, it is characterized as multispectral[2] and is often associated with devices such as abridged spectrophotometers. When the bandpass is relatively narrow, between one and five nanometers, it is characterized as hyperspectral[3] and associated with devices such as spectrophotometers and monochromators. Generally, as the bandpass narrows, the accuracy and precision of a measurement increases and more useful and specific data can be extracted.

3. CREATING THE BANDPASS

A bandpass may be described as a continuous portion of spectrum bandwidth where the spectral separation between two points attains 50% of its peak transmission value, or the full-width at half maximum (FWHM). This can be termed the spectral resolution. The center wavelength is defined as the wavelength midway between these two points, but is not always identical to the wavelength with the highest transmission. Related to spectral resolution is spectral sampling interval, or the interval, in wavelength units, between data points in the measured spectrum[4].

Generally, three mechanisms are used to create bandpasses of visible light for imaging systems, filters, gratings or prisms. A fourth mechanism, based upon an interferometer, may also be used. A fifth mechanism, monochromatic light as might be produced by a laser, may also be used, though this technique is not currently considered a commercial option. A wide variety of options are available with regards to these mechanisms, many more than can be covered by this document. Filters may be, for example, of the interference type and constructed from thin films with fixed bandpasses and transmission characteristics. Or they may be constructed from birefringence or liquid crystals, capable of rapidly and precisely changing wavelength selection via acousto-optic signals. Gratings may be reflective or transmissive in nature and constructed with various rulings to create dispersions of different bandwidth ranges or spectral resolutions. They may also be combined in optical series or with other components, such as prisms or filters, to attain very exact bandpass and transmission characteristics.

One characteristic of note with regards to the bandpass is its actual shape. For example, a typical, well made thin film interference filter with a nominal FWHM bandpass of 20 nm centered at 560 nm actually allows transmission between 535 nm and 585 nm, while maximum energy transmission is truncated to 60% of the wavelengths actually transmitted at FWHM[5]. When graphed, the sloping sides of such an interference filter-generated bandpass contrasts with a similarly wide bandpass created by a grating, where a different mechanism, often a linear sensor, defines and truncates bandpass edges, creating a sharp, well-defined edge between bands. Therefore, to achieve a specific sampling coverage, in the case of interference filters, for example, it may be necessary to utilize a spectral resolution that differs from the sampling interval, while the interval and resolution of a grating-generated bandpass may more often be identical.

Physically, color perception varies according to the wavelength of the visual stimulus. Perceptually, when the bandpass is narrow, the resulting perceptions are associated with pure or highly saturated color and, as the observed bandpass widens, the color appears less pure. These perceptions, however, are non-linear (ie: two bandpasses of equal width may not appear equally saturated) and observers with normal color vision often respond differently to the same specimen, so what is pure color to one may not be perceived that way by another observer[6].

With regards to bandpasses, human color perception may be determined, specified and communicated in a variety of ways. In its simplest and most abstract form, varying the density of one hue, for example shades of gray, can effectively simulate color perception and this situation may therefore be considered a single, panchromatic bandpass capable of rendering different "colors" via density differences. And, by deliberately substituting one or more false colors or tones in an otherwise uniform density presentation, specific visual information may be highlighted or emphasized, thereby maximizing communication with minimum colorimetric effort.

About 200 years ago Young postulated human color perception was part of a physiological system that included three different light receptors in the eye[7]. This trichromatic model may be described as three wide, organic-based bandpasses, spread across the visible bandwidth range. About 55 years later Maxwell introduced a mechanical analog of the trichromatic model when he demonstrated that most colors can be matched by both varying the intensity of and superimposing three separate light sources, known as primaries (ie: bandpasses), in a process known as additive mixing[8]. Variations on Maxwell's three bandpass system evolved into today's color measuring systems that include colorimeters and color scanners, and "true color" rendering methods such as color photography, process color lithography and color television.

While effective and useful, the three bandpass system, whether based upon optical filters, gratings or prisms for measurement or dyes, inks or phosphors for rendering, has significant limitations. These include an inability to express all colors perceptible by humans and, in the case of measuring systems, an inability to distinguish metamerism, a visual phenomenon characterized by two specimens that match under some viewing conditions and do not match under others[9].

Therefore, sophisticated schemes based upon systems with more than three bandpasses are necessary to make measurements or render images that encompass the full gamut of humanly perceptible colors[10].

4. MEASURING THE BANDPASS

Hyperspectral imaging is associated with large amounts of data moving at high rates and two critical components, the light sensor and the analog to digital converter (ADC), form an electronic "choke point" that determines the ultimate quality and speed of any measurement or device. Because of recent advances in both sensor and ADC technology, it is now possible to create relatively low-cost devices that are able to analyze and digitize hundreds of spectral bands from thousands or millions of image pixels at very high speed.

While it is possible to utilize vacuum tube based photo-multipliers as light sensors to make hyperspectral measurements, this technology is usually applied in very limited circumstances and is generally not considered practical for most imaging applications working in the visible range. Therefore, the discussion will be limited to silicon-based solid state technology, specifically charged coupled devices (CCD) and complementary metallic oxide semiconductor (CMOS) based sensors. Both of these technologies offer adequate sensitivity in the visible range and can be fabricated into highly reliable components that exhibit specific spatial and performance characteristics necessary to perform hyperspectral measurements.

Adequate sensitivity in the visible range is often defined by the photo-dynamic range of the sensor, which typically outputs a continuous analog signal that must be digitized into discrete levels by an ADC. This dynamic range may be represented as a log ratio of an individual sensor element's electron well depth to the readout noise in decibels, dB. For example, a sensor element or sensor pixel with a well depth of 85,000 electrons and a readout noise of 12 electrons would have a dynamic range of 20log (85,000/12) or 77 dB. This ratio gives an indication of the number of digitization levels that are appropriate for a given sensor. Stated as a power of 2, a sensor with a well depth of 35,000 electrons and 15 electrons of noise would yield a ratio of log(35,000/15)/log(2) = $2^{11.188}$, or 2,333 levels, and a 12-bit ADC system with 4,096 levels would be adequate to fully represent the light sensing capability of the sensor. A sensor with a well depth of 150,000 electrons and 15 electrons of readout noise would have a ratio of 10,000 or about 80 dB and a 14-bit ADC system with 16,384 levels would be adequate. To put these numbers into perspective, it has been determined that humans can resolve about 8,200 discrete levels (or 2^{13}) of chromaticity information when the *Just Noticeable Color Difference* is understood as $\Delta E^*_{ab}=1.0$[11]. These levels may run continuously over a perceived brightness range of 10 log units[12] that varies in luminance (lux) from a moonless night (10^{-3} lux) to noonday sun (10^{5} lux)[13]. To draw a distinction, photographic film covers about a 2.3 log unit exposure range[14] with a typical photographic subject exhibiting a contrast range of 160:1 and an extreme case ranging as great as 1000:1. But lens flare and scattered light from inside the camera often reduces an average subject brightness range of 160:1 to as little as 35:1[15].

The spatial configuration of a light sensor used to measure bandpasses is determined by the type of hyperspectral component integrated into the system. In a system where the size of the individual pixels that comprise the image are determined by optics or mechanisms external to the component, it is usual to find linear light sensors where the light from individual image pixels is dispersed along a single sensor axis. The size of the sensor's pixels determines the spectral resolution of the bandpass created. An example of such a configuration would be a crossed Czerny-Turner spectrophotometer. An alternative design, often associated with imaging spectrographs, uses a two-dimensional area light sensor. Here the dimension of the sensor's pixels along the Y-axis is associated with the spatial resolution of the image pixel and the dimension of the sensor's X-axis pixels is associated with the spectral resolution of the system.

5. CURRENT HYPERSPECTRAL APPLICATIONS AND SYSTEMS

Current hyperspectral imaging applications can be broadly categorized as scientific, medical or military, with a few scientific applications utilized commercially. The scientific, commercial and military applications for hyperspectral imaging are often associated with airborne or on-orbit remote sensing systems, while medical applications generally utilize laboratory-based systems. There are also a limited number of what may be termed academic prototype applications and systems utilized for artwork or artifact analysis and psychological studies.

While the specific practical imaging device to be discussed below is limited to the visible portion of the EM spectrum, hyperspectral imaging applications in general often cover a much broader bandwidth. This may range from the ultraviolet (UV or 190-400 nm), through the visible (VIS or 360-830 nm) and well into the near, short, medium and long, or thermal, infrared bands (NIR, SWIR, MWIR, LWIR or 700 nm – 13.5 microns).

The concept behind remote sensing is straightforward. All natural and man-made materials on the surface of the Earth have a unique spectral signature of reflected light from the sun[16]. These signatures are often collected and stored in the form of a data cube, where the X and Y axis encode spatial information and the Z axis encodes spectral data. Therefore, creating a graphical representation or characteristic curve of any pixel of any remotely observed image is possible by skewering the Z axis of any XY coordinate pair of the image and then graphing the resulting data by plotting it on a separate XY graph. On the second graph the observed radiant energy intensity follows one axis and the distribution of this energy, according to wavelength, follows the opposing axis[17]. By extension, this technique can be applied in a laboratory, industrial or commercial setting by using artificial light sources to illuminate the material of interest.

Many remote sensing systems are based upon a so-called pushbroom design[18]. In this design optics focus a strip of the target onto a slit in the sensor apparatus. The slit creates an aperture that forms the target strip into a segment of the image called a line. This line is projected into an imaging spectrograph that uses an area sensor to break the line into image pixels along one axis of the sensor. Simultaneously a mechanism such as a grating is used to disperse each image pixel along a row of sensor elements on the opposing axis of the spatial elements, creating bandpasses whose width is linked to the physical size of the sensor's pixels and the dispersing characteristics of the grating. The motion of the airplane or satellite hosting the hyperspectral imaging system automatically and continuously brings strips of the target being imaged into the system's field of view. The combination of optics and altitude of the flight vehicle determines the width of the observed strip, with the ratio of the observed strip's width to entrance slit/number of sensor pixels determining the spatial resolution of the apparatus. By optically varying the width of the observed target strip projected onto the sensor's slit, the spatial resolution of the system can be manipulated independently of the spectral resolution of the system.

Typical airborne remote sensing systems include the 288 band AAHIS, Advanced Airborne Hyperspectral Imaging Spectrometer, manufactured by Science Application International Corporation with spectral coverage between 433 nm and 832 nm, and the 128 band TRWIS-A, TRW Imaging Spectrometer, manufactured by TRW, with spectral coverage between 430 nm and 850 nm. TRW also built Hyperion for NASA, a 220 band, space-based remote sensor currently on-orbit, with coverage from the visible to SWIR.

Using remote sensing and data cubes, it is possible, for example, to facilitate mineral exploration, environmental research or map the location of various minerals found on the earth's surface. Specific functions such as identifying plant species, locating heavy metal contamination from abandoned mines, examining the health of desert vegetation, performing climate change studies, monitor the health of coral reef eco-systems and even track grizzly bear habitats[19] are possible. Well known military applications include the ability to remotely distinguish camouflaged military vehicles such as tanks from the foliage that might be used to conceal them and the identification of rocket exhaust plumes that could indicate an impending nuclear strike. Hyperspectral medical applications include imaging molecular, genetic and living cell structures and automatic identification of cell and tissue types, especially as related to the Human Gene Project. Non-imaging commercial applications for hyperspectral technology include automated quality control based upon catching materials that are out of a range of accepted colors prior to final assembly.

An interesting academic hyperspectral imaging project was the interference filter-based hyperspectral camera and images created by David Brainard and his UPENN colleagues[20]. Another group producing images from nature, the team of William Smith and his colleagues from Washington University in St. Louis, used a hyperspectral imager called the Digital Array Scanned Interferometer, or DASI[21]. And, of historical note, there is the Smithsonian Institution Project for the Preservation of the Star Spangled Banner[22]. This project uses a purpose-built system working with infrared bandpasses at hyperspectral resolutions to image the flag which inspired Francis Scott Key to pen the words to the Star Spangled Banner, in order to determine levels of moisture and non-polar oils contamination in the huge wool flag.

6. STANDARDS

Until this point in the presentation the mechanics of hyperspectral imaging and "traditional" hyperspectral applications have been discussed. However, there is clearly a disconnect between current hyperspectral imaging technology and applications and "traditional" colorimetric imaging technology and graphical reproduction applications. Hyperspectral imaging provides techniques for capturing data useful for scientific analysis and this data can also be applied to graphical applications, but it is not. And traditional imaging technology has established standards able to use data generated via hyperspectral imaging techniques, but this has not been the case. By applying traditional colorimetric standards to hyperspectral imaging, a new graphical imaging technique can be established. This technique would rely upon faster and more sophisticated hardware to process and manage the large quantities of data associated with both multispectral rendering and hyperspectral imaging. Simply stated, instead of attempting to develop hybrid imaging paradigms and procedures that truncate the mountains of data, use faster hardware to both manage the data flow and apply known standards in novel ways.

There are three groups of colorimetric standards that can immediately be applied to hyperspectral imaging to improve the process of color measurement and color reproduction. One grouping of standards is the ASTM (American Society for Testing and Materials, West Conshohocken, PA) standards E 1164-94, *Standard Practice for Obtaining Spectrophotometric Data for Object-Color Evaluation*, and E 308-95, *Standard Test Method for Computing the Colors of Objects by Using the CIE System.* Another grouping is the CIE (Commission Internationale de 1' EclairageWien, Austria) standards CIE 15.2-1986, *Colorimetry, 2nd Edition* (ISBN 3 900 734 00 3), and ISO (International Organization for Standardization, Geneva, Switzerland) /CIE 10526: *Colorimetric Illuminants* and ISO/CIE 10527: *Colorimetric Observers*. The ASTM standards are a truncated variation of the CIE standards, which decompose a color into saturated monochromatic components of known bandwidth, apply mathematical operators to each component and integrate the results to arrive at a set of values characterizing the color.

The ASTM standards, in turn, are the basis for a third, even more abridged graphic arts standard for measuring individual color specimens, CGATS.5-93, *Spectral Measurement and Colorimetric Computation for Graphic Arts*. The CGATS standard is published by The Committee for Graphic Arts Technologies Standards. This group is accredited by the Image Technology Standards Board, ITSB, of ANSI (American National Standards Institute, Washington, DC), and closely associated with the technical committee ISO/TC130 Working Group (CGATS, c/o NPES, The Association for Suppliers of Printing, Publishing and Converting Technologies, Reston, VA).

By agreement the CIE, since 1913, has developed standards regarding how color is measured and described. The underlying premise of the CIE system, referred to as CIE31, is that the stimulus for color is provided by the proper combination of a source of light, an object, and an observer[1]. In 1931 the CIE introduced standardization of the source and observer in the form of tables calibrated at one and five nanometers, and also provided the methodology to derive numbers that provide a measure of a color seen under a standard source of illumination by a standard observer. This standardization forms the foundation of modern colorimetry and is based upon spectral measurements using hyperspectral, or one or five nanometer wide bandpasses. CIE-31 uses a specimen's Characteristic Curve for the calculation of Tristimulus Values X, Y, and Z and Chromaticity Coordinates x and y[23]. The CIE-76 recommendations establish transformations of the X, Y, and Z Tristimulus Values into nearly visually uniform color scales such as CIELAB, and also established a method to quantify differences between two color specimens[23].

Chromaticity Coordinates x and y are the result of linear transforms of X, Y and Z and, when plotted, locate visible colors in a two-dimensional horseshoe-shaped graph representing the CIE 1931 xyY color space. While only two of the three dimensions of color are shown on a Chromaticity Diagram, a three-dimensional version of the diagram is often made by plotting an axis for Y rising from the illuminant point of the diagram[24].

CIELAB (L*a*b*), the result of a non-linear transformation of X, Y and Z, is an opponent-type system. This system assumes a color cannot be red and green at the same time, or yellow and blue at the same time, though it can be both red and yellow (ie: orange) or red and blue (ie: purple). Therefore, a specimen's redness or greenness can be expressed as a single number, called a*, which is positive if the color is red and negative if it is green. It follows that yellowness or blueness is designated by the coordinate b*, positive for yellow and negative for blue. The third coordinate, L*, is the lightness of the color. The CIELAB color space is expressed graphically by plotting in rectangular coordinates the quantities L*a*b*[25].

Until now the full benefit of the CIE system has not been taken advantage of by the graphic arts industry with regards to image scanning. Even manufacturers of printing inks, photographic dyes and color monitors for computers and televisions utilize ASTM-based standards, not the more complex and exact CIE standards.

The less stringent ASTM industrial standards for color measurement truncate the wavelength range between 360nm and 780nm and support bandpasses of 10nm and 20nm for a variety of illuminants. The least stringent standard for color measurement, CGATS.5-93, also truncates its spectrum between 360nm and 780nm, but supports only 10nm and 20nm wide bandpasses for one type of illuminant.

In practice, another standard related to how color is specified is required to successfully apply hyperspectral imaging to graphic arts applications. This standard has to do with data file formats. Currently, the TIFF file format[26] is the only generally used format that allows colorimetric information to be save as CIELAB-encoded data. All other formats save colorimetric data as Red, Green, Blue (RGB) or Cyan, Magenta, Yellow, Black (CMYK) data. However, this format allows the CIELAB-encoded data to be saved only as eight bit integer data, limiting the colorimetric and dynamic range of the file. It will therefore be necessary to upgrade the TIFF format to save data in CIELAB or XYZ, 16-bit format to immediately take full advantage of hyperspectral scanning and CIE colorimetric standards. An archival image format for pixel spectra data should also be developed along the lines suggested by Dr. Friedhelm König of Agfa in the inaugural issue of the newsletter *Spectral Vision*[27]. This format should be lossless and rely upon improved computer hardware to transform the data in real-time from spectra to device dependent or device independent colorimetric values.

7. A PRACTICAL DEVICE

The following schematics (Figs. 1A, 2B, 3C, 4D, 5E) illustrate a graphical scanner able to capture images in accordance with scientific, device independent color standards. It is offered as a proof of concept design verifying the feasibility of digitizing and saving traditional graphic arts originals using hyperspectral techniques, CIE color standards and commercial file formats. As a proof of concept system, it is not optimized for speed or extreme spatial resolution.

Rather, it is to demonstrate to the sophisticated reader that current colorimetric standards can be applied, in a practical way, to the problem of capturing and saving graphical images hyperspectrally.

The device is a flatbed scanner. An open aperture XY translation stage (Fig. 5E, 37, 38 and Fig. 1A, 2B, 2, 3) is used to hold an image (Fig 1A, Fig 5E, 12) mounted on a glass plate (Fig. 5E, 39) and step it through a fixed optical path, comprised of a focusing lens and a turning mirror (Fig. 2B, 29, 30). The source of illumination (Fig. 2B, 23), the output of a Xenon white light (Fig. 2B, 24), is directed through a diffuser (Fig. 2B, 26) and to the optical path via a fiber optic cable (Fig. 2B, 25). By repositioning the fiber cable (25), reflective or transmissive originals may be used. Servomotors (Figs. 1A, 2B, 5E, 10, 11) and amplifiers (Fig. 1A, 6,7), under the control of the host computer (Fig. 1A, 1) and scanner application software (Fig. 1A, 22), are fed digital commands via control lines (Fig. 1A, 4, 5, 8, 9). These commands cause the system to step the translation stages according to parameters selected by the operator, via a graphical user interface. These parameters include a variety of CIE-specified illuminant and observer colorimetric values and various pixel spatial resolutions. The operator also selects "white" and "black" points for calibration purposes and what portion of the scanner's bed to step through the optical path. Upon issuing the start command, the scanner's application software (22) moves the bed in a three-step cycle that systematically brings the image being scanned through the optical path. The cycle first steps the stages to the next logical location, allows them to settle, and then causes the system to capture and transmit, in parallel, the pixel light (28) to the light sensors (Fig. 4D, 35) and other electronic components. This cycle typically takes 10 milliseconds and the on-board computer and digital signal processors perform all colorimetric calculations and transformations in real-time. As the software concludes scanning each image line, it automatically causes that portion of the image to be displayed on the system's monitor.

Image pixels are created by focusing portions of the original transmitted or reflected light (Fig. 2B, 28) into the fiber optic array (Figs. 1A, 2B, 3C, 13). The individual fibers (Figs. 1A, 2B, 3C, 4D, 14) are fabricated with an outer cladding (Fig. 3C, 31) about 125 microns in diameter and an inner core (Fig. 3C, 32), nominally 50 microns in diameter (Fig. 3C, 41). The fibers are positioned nominally at fixed center to center intervals of 200 microns (Fig. 3C, 40) by machined grooves (Fig. 3C, 42) in the array's harness and the pixel light is directed to individual hyperspectral analyzers (Fig. 1A, 2B, 4D, 15) via the fiber's core (32). When this fiber configuration is matched to a 4x magnifying and focusing lens, varying the size of the step allows the system to create pixels with a nominal "scanning resolution" of 508, 1,016, or 2,032 pixels per inch, with a true optical resolution of 12.5 microns, or 2,032 dpi. In practice, the pixel light (28) or white light (Fig. 2B, 27, in the case of calibrating the device) is directed, via collimating and focusing mirrors (Fig. 4D, 33) inside the analyzer, to a grating (Fig. 4D, 34). The resulting dispersed light (Fig. 4D, 36) is then focused on the internal linear light sensor (35), thereby breaking the pixel light into the narrow bandpasses needed for calculating CIE colorimetric values. The dimension of the sensor's elements and the dispersion of the pixel's light into a spectrum determine the exact size of the bandpass, in nanometers, created by each individual sensor element. The system's spectral range is determined by the grating's (34) ruling.

Via the control lines (16), the analog output of the light sensors (35) is directed to the Multifunction Data Acquisition Cards, or MDACs (Fig 1A, 17), which are attached directly to the host computer via motherboard connectors (Fig. 1A, 20). The MDACs include analog to digital circuits (Fig. 1A, 19) and digital signal processors (Fig. 1A, 18) able, under the control of the scanner application software (22), to transform the output of the hyperspectral analyzers (15) into digital data that represents colorimetric characteristic curves and CIE XYZ and LAB values. Finally, the image pixel's colorimetric values are formatted and stored in the host computer as CIELAB-encoded TIFF data files (Fig. 1A, 21). Such files can be opened and manipulated by many commercially available graphical programs, such as Adobe PhotoShop.

Sample images scanned by the above-described device are available for downloading from the web site www.spectralmasters.com. Please contact the author directly for a larger selection of images, available on CD-ROM. As a courtesy, attendees of this symposium who provide a 35mm slide will receive a complimentary scan of the image.

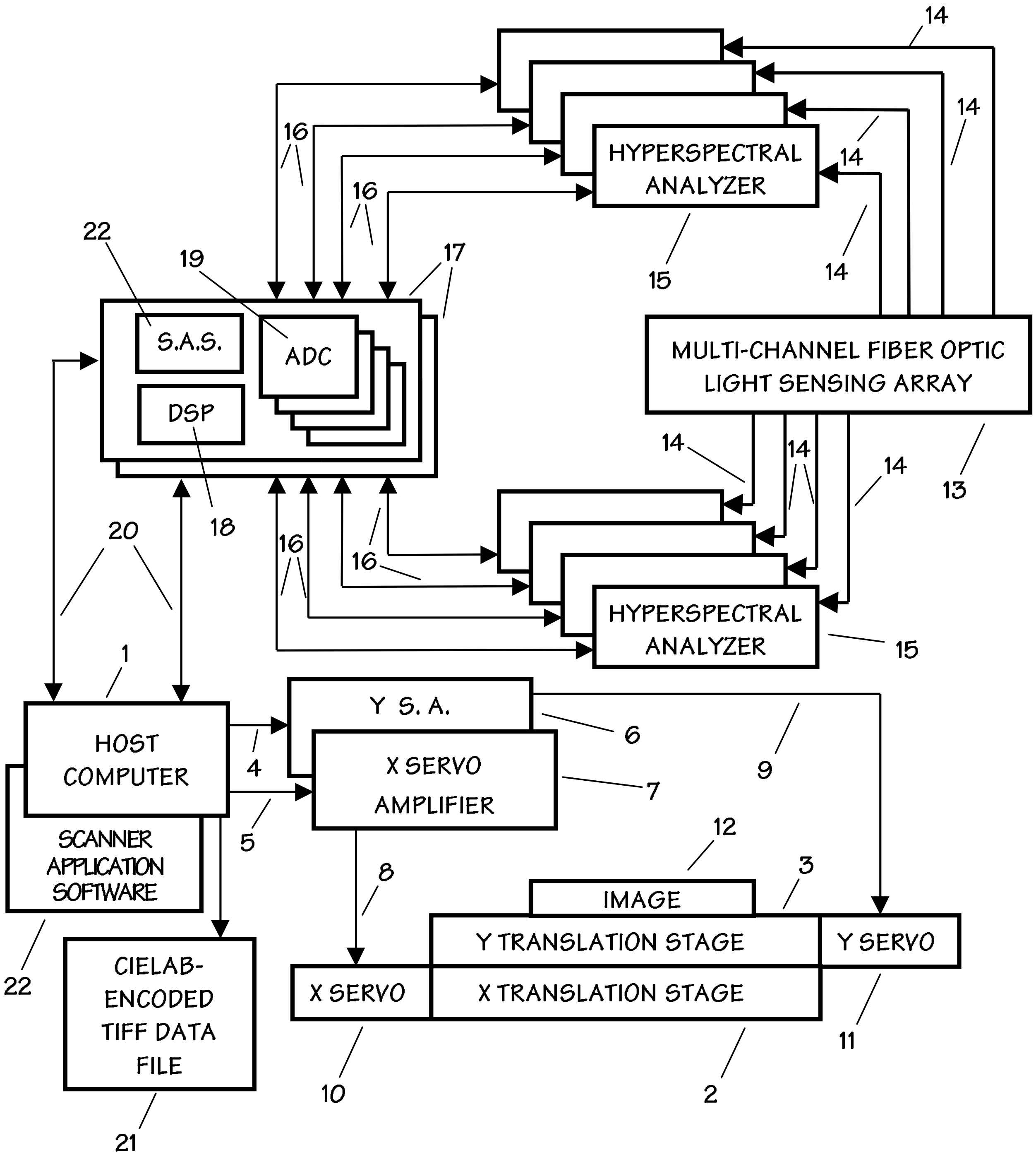
14
14
14
16
14
HYPERSPECTRAL ANALYZER
16
14
22
15
14
19
17
S.A.S.
ADC
MULTI-CHANNEL FIBER OPTIC LIGHT SENSING ARRAY
DSP
14
14
14
13
18
20
16
16
HYPERSPECTRAL ANALYZER
15
1
Y S. A.
HOST COMPUTER
6
4
X SERVO AMPLIFIER
9
7
SCANNER APPLICATION SOFTWARE
5
12
8
3
IMAGE
Y TRANSLATION STAGE
Y SERVO
22
CIELAB-ENCODED TIFF DATA FILE
X SERVO
X TRANSLATION STAGE
11
10
2
21

FIG. 1A

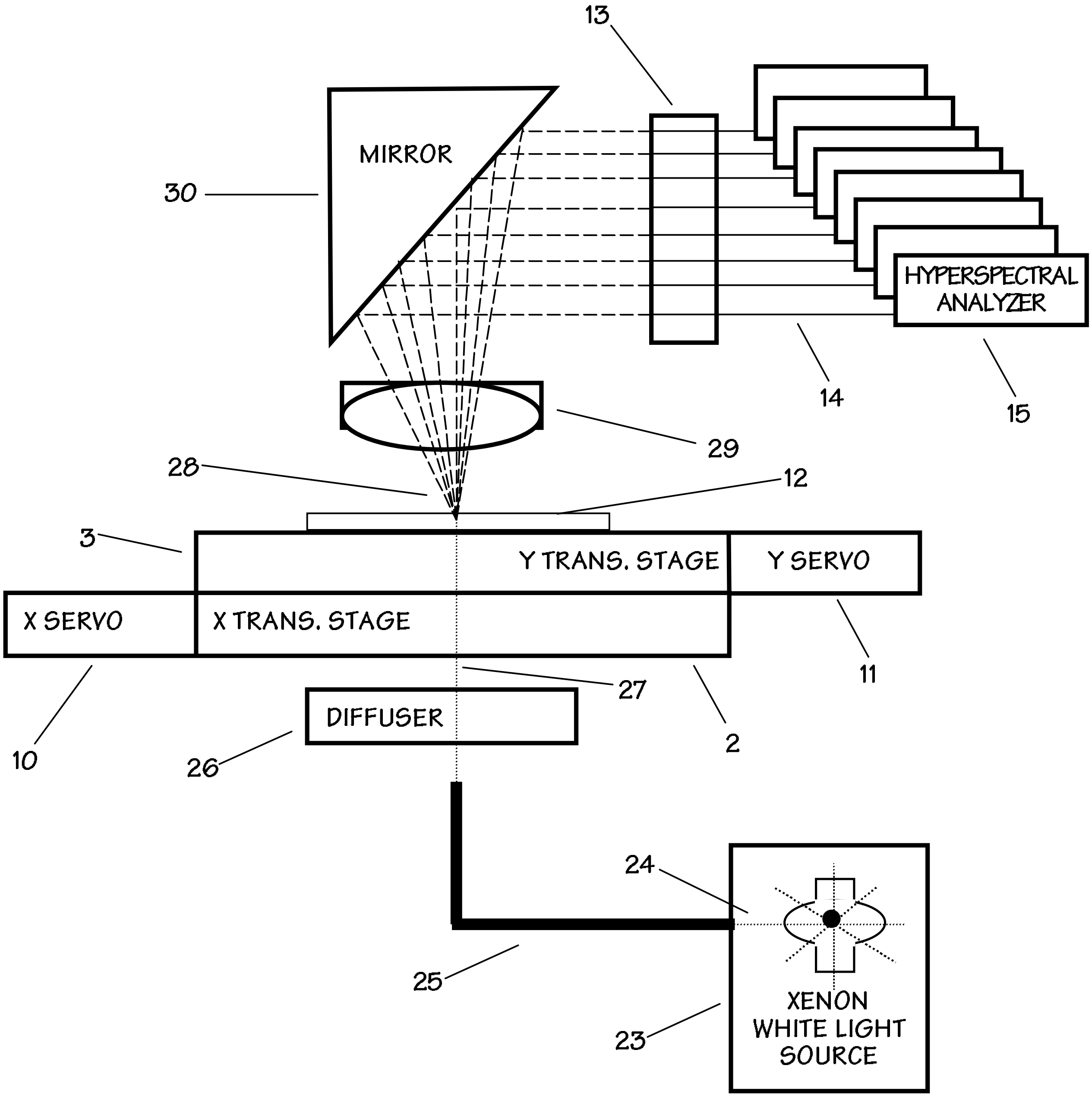
13
MIRROR
30
HYPERSPECTRAL ANALYZER
14
15
29
28
12
3
Y TRANS. STAGE
Y SERVO
X SERVO
X TRANS. STAGE
11
27
DIFFUSER
2
10
26
24
25
23
XENON WHITE LIGHT SOURCE

FIG. 2B

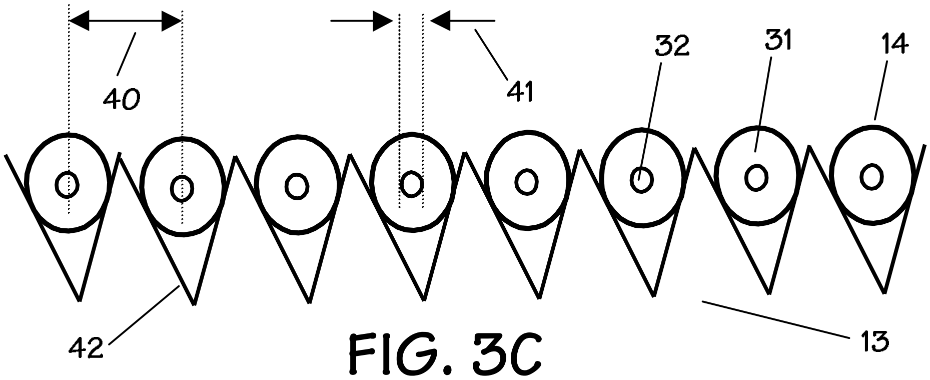

FIG. 3C

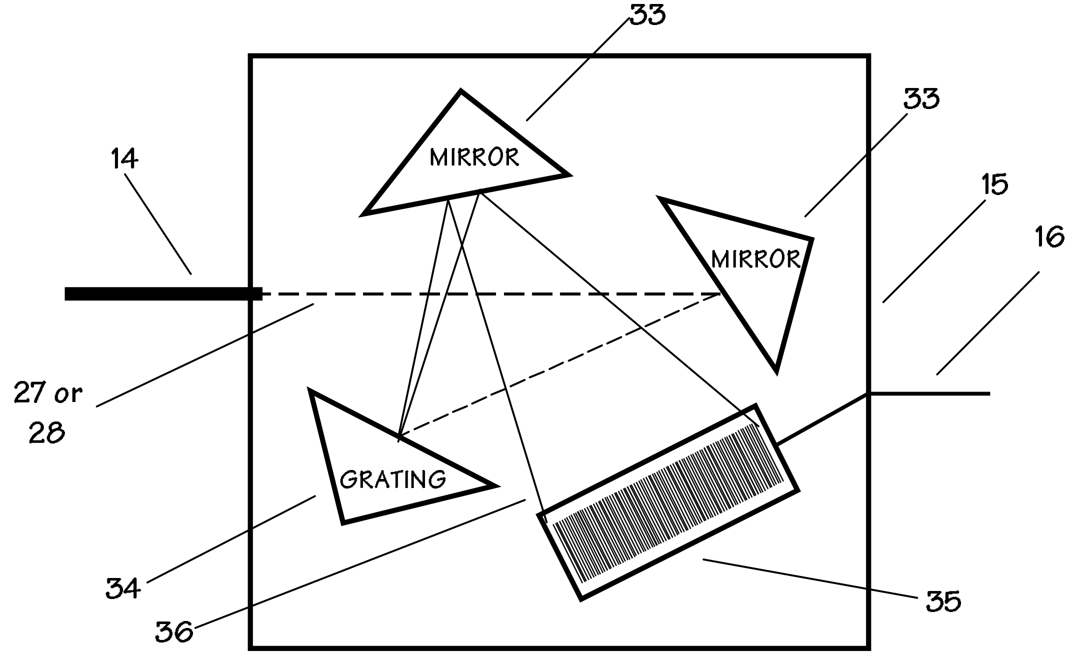

FIG. 4D

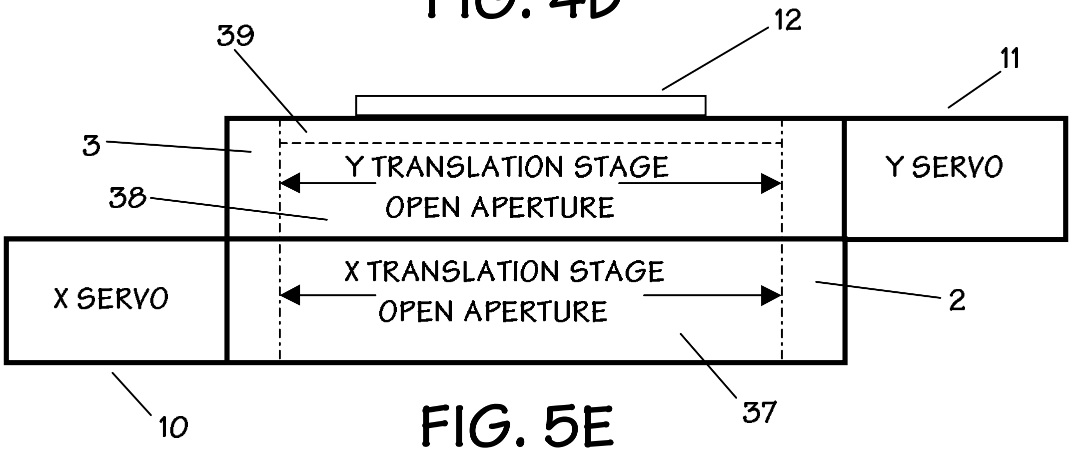

FIG. 5E

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