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COLOR IN PHOTOGRAMMETRIC REMOTE SENSING

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ABSTRACT

A photogrammetric process using "color" as a physical measurement of topographic objects of interest may be denoted as "photogrammetric remote sensing", where the photogrammetric determination of the "where" and "how large" merges with the remote sensing ideology of automatically classifying the "what" of topographic objects.

As digital cameras are beginning to enter into photogrammetric practice, a dimension of complexity is being added to photogrammetry that has been a main concept in remote sensing for a long time. While color aerial photography simply is being produced with three perfectly co-registered emulsion layers, digital images can be obtained in a variety of different approaches. High-resolution panchromatic imagery may be combined with lower resolution color images. Color may also get created by sequentially producing its components, thereby introducing a need to eliminate geometric differences. The use of color in analyzing terrain has been a traditional topic in remote sensing. In photogrammetry the digital sensors present a new need to understand the coloration alternatives. We therefore present the various alternatives to sense color at the intersection of photogrammetry and remote sensing. We then proceed to address the different "coloration" schemes combining high resolution black-and-white pixels with the lower resolution color pixels and we take a look at the differences between the color images obtained from various approaches. The geometric resolution of the resulting "pan-sharpened" color images is of interest.

<u>Key Words</u>: Color imagery, coloration, pan-sharpening, fusion, photogrammetry, remote sensing

1. COLOR SENSING IN REMOTE SENSING AND PHOTOGRAMMETRY

Color has great importance in remote sensing and is considered the primary object of the physical sensor measurements made about the terrain surface and its cover. Remote sensing has traditionally been interested in objects with an extended surface such as agricultural or other geo-science entities. In photogrammetry, the focus is on geometric accuracy and detail as a feature of point- and line-like objects, which is reflected in the panchromatic information of an image. As a result, color has been traditionally of lesser importance.

However, color is of growing interest in photogrammetry as well, as automation of the image interpretation function evolves. In many regions of the world, photogrammetry has begun to employ color film as standard source material, as reflected by the fact that film manufacturers over the last decennium report a doubling of the sales of color film at the expense of the use of black & white film. At the same time photogrammetric film scanners have become challenged with the need to resolve the subtleties in color of the film sources. In the transition from analog film imagery to digital sensing, however, color is becoming a growing challenge, since the focus on geometric accuracy and detail continues to exist, but color information is also of interest. How can high geometric accuracy and resolution be combined with color information in an affordable manner?

We discuss in this contribution various technologies to create digital color images. Most prominently are procedures where a high-resolution panchromatic image is being "colorized" by lower resolution color data. A factor 3 to 5 between the geometric resolutions of panchromatic and color sensing may be acceptable.

2. SENSING COLOR AND COLORATION SCHEMES

2.1 Color Sensing

Various approaches to color sensing have been proposed. Recent satellite missions and aerial digital camera solutions have demonstrated that color can be obtained by:

- Ψ Simultaneous collection of multiple colors per pixels using linear push-broom detector arrays, all at one geometric resolution (as in the Landsat-approach and in the Leica ADS40 aerial camera, Leica, 2002);
- Ψ Simultaneous collection of panchromatic images, each with a color filter, as presented by Positive Systems (2001)
- Ψ Simultaneous collection of panchromatic and color data with linear arrays CCDs, but at different geometric resolutions (the standard satellite approach in the IRS-, Ikonos-, Digital-Globe- and other systems);
- Ψ High geometric resolution panchromatic area CCD sensing in combination with lower resolution area CCD color sensing using the Bayer pattern (no commercial solution currently being offered);

- Ψ High geometric panchromatic area CCD sensing in combination with lower resolution area CCD sensors using different filters (the Z/I Inc DMC aerial camera, Z/I Inc, 2002);
- Ψ Color area CCD using the Bayer pattern, and no separate higher resolution panchromatic sensor (the aerial camera solutions by Emerge, 2002 and by Enerquest, 2002).

The new aerial digital cameras by Leica and Z/I are proposed as remote sensing sensors separate from the traditional aerial film cameras. As a result these cameras offer 4 spectral bands, including an infrared channel. They are considered to address both the needs of the photogrammetric as well as of the remote sensing users. This encourages us to speak about a "photogrammetric remote sensing" concept.

2.2 Coloration of High-Resolution Pan-chromatic Pixels

Of interest to us is the manner in which color is being assigned to each high-resolution pixel. Traditionally this was not an important topic since multi-spectral scanning provided each pixel with multiple color values. However, with color being scanned at one geometric resolution and by one sensor, and the panchromatic information being collected at a higher geometric resolution and with a separate sensor, the issue emerges of how to "color" the black-and-white panchromatic pixels. A standard "coloration" scheme has emerged in which the panchromatic pixels represent the high geometric information and thus the "intensity" band in a color space, whereas the color pixels represent the hue and saturation or similar such bands. More generally, coloration can be accomplished in various ways as discussed below.

2.3 Sensing Color

2.3.1 Three CCDs

Each of three CCDs has its own color filter for red-green-blue (RGB), and each CCD images with a different perspective (see Figure 1).

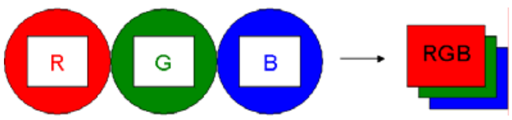


Figure 1: Three images are being produced, one by each of the 3 CCDs, and represent the RGB-channels. These images must be co-registered.

The problem with this approach is the need to overcome the mis-registration between the RGB-channels. Registration typically is being accomplished via matches of the R-G and G-B-channels.

2.3.2 CCD with Color Beam Splitter.

Figure 2 illustrates the use of a beam splitter to produce 3 images with the same geometry. The issue is the reduced amount of light arriving at the sensor.

2.3.3 Single CCD with Spinning Wheel Disk Filter

Figure 3 suggests the spinning wheel to obtain color in 3 separate images, taken sequentially. This limits the geometric quality since the images are taken with separate exterior orientations during flight.

2.3.4 Bayer Pattern CCD for Color Information

As proposed by Bayer (1976), a single area array CCD is being used with a filter in front of every CCD-element. Figure 4

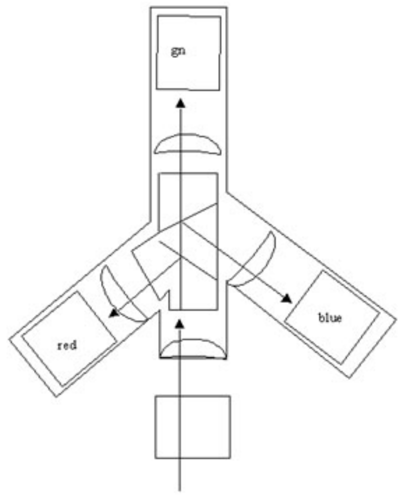


Figure 2: Beam splitter to obtain color in one simultaneous step (from www.howstuff works.com). There exists a single geometry. Registration matching is not needed.

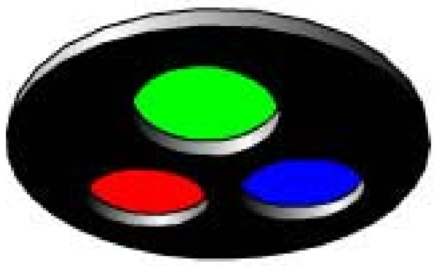


Figure 3: The so-called "spinning wheel" to sequentially create red, green and blue component images, taken at slightly different times, since the filters must be rotated into place in front of the lens.(from www.howstuffworks.com).

R	G	R	G	R
G	B	G	B	G
R	G	R	G	R
G	B	G	B	G
R	G	R	G	R

Figure 4: The Bayer pattern is obtained by placing red, green and blue filters over each element of a CCD as shown. Green is being favored over red and blue.

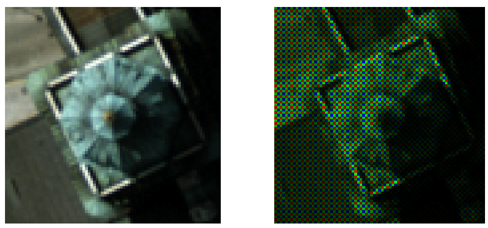


Figure 5: A simulated illustration of a Bayer pattern image. Left is a conventional color image with 81 x 81 pixels. To the right is the computed Bayer pattern image with alternating r, g and b pixels in the pattern shown in Figure 4. That is the raw output of the color CCD. Reconstruction of the final color image is called demosaicking.

illustrates the basic concept and shows that green has twice the number of red- and blue-pixels. Figure 5 is a simulation on 81 x 81 pixels of a color image using this basic idea. At issue is the creation of the color image from the sensed pattern. This is denoted as “demosaicking” (Adams, 1995, 1997).

2.3.5 Foveon X3 CCD Technology
Foveon has developed a digital analogy of color film (Figure 6). We quote from the company’s web site at www.foveon.com:
"The revolutionary design of Foveon X3 image sensors features three layers of photo detectors. The layers are embedded in silicon to take advantage of the fact that red, green and blue light penetrate silicon to different depths, forming the world's first full-color image sensor. Foveon X3 technology features the first image sensors that can capture red, green and blue light at every pixel."

The largest CCD size currently is at 2268 × 1512 × 3 pixels. This may be too small to be very useful for aerial imaging.

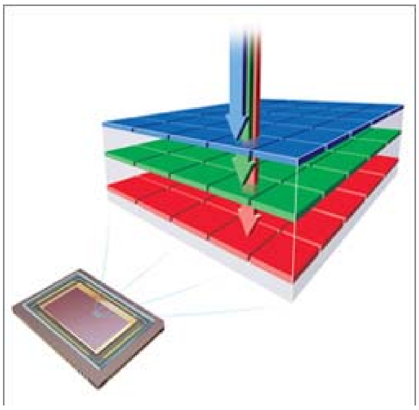


Figure 6: Foveon-Sensor to produce color digitally with three layers (© Foveon, www.foveon.com)

2.4 Assessing the Differences in the Approaches

We are interested in assessing the merits of these different schemes. For instance, the Bayer pattern of an area array affects the geometric resolution of the resulting image. A 4000 pixel by 4000 pixel array consists of 4 independent sub-images at 2000 x 2000 pixels each, namely one array of 2000 x 2000 pixels in red and another in blue, and two images with 2000 x 2000 pixels in green. What is the panchromatic geometric resolution? And how does the approach with one higher resolution panchromatic area CCD plus multiple lower resolution panchromatic sensors, each equipped with a color filter, compare with color from the Bayer pattern?

Geometric resolution is often described by the so-called “edge response”, and this may typically be defined by the size of the basic pixels from which a color image is being derived. Color quality, on the other hand, is affected by the uniqueness of the color assignment along the edge of a region. Context-based coloration would thus be needed to avoid a “rainbow” effect along the edges of objects. We will discuss a novel context based scheme for “coloration” of higher resolution panchromatic pixels.

3 COPING WITH DIFFERING GEOMETRIC RESOLUTIONS

3.1 Methods of Merging Color at One and B&W at another Resolution

The most popular techniques are IHS (Intensity, Hue, Saturation), PCA (Principal Components Analysis), arithmetic combinations and wavelets fusion (Zhang Y., 2002). Note that the term “fusion” is being used for this process.

3.1.1 HIS and Other Color Transforms
For this kind of fusion, the RGB channels are separated into spatial (intensity) and spectral (color) information. Commonly used color transforms are IHS, LAB, YIQ and YUV. The process works as follows: The input image gets transformed into the IHS space, the resulting intensity channel gets replaced by the panchromatic image with its higher resolution. Then a reverse color transformation is performed. This technique has become a standard fusion procedure.

3.1.2 PCA Concept
Performing a Principal Component Analysis (PCA) on the input RGB image leads to PCA-channels. The first such channel is being replaced by the high resolution panchromatic image, and a reverse transformation produces the color image.

3.1.3 Arithmetic Combinations
Using arithmetic operations, such as multiplication, division, addition and subtraction of the various input channels is feasible. An example is the addition of the three multi-spectral images to a sum, then dividing each spectral channel by this sum image and multiplying each quotient by the high resolution panchromatic information.

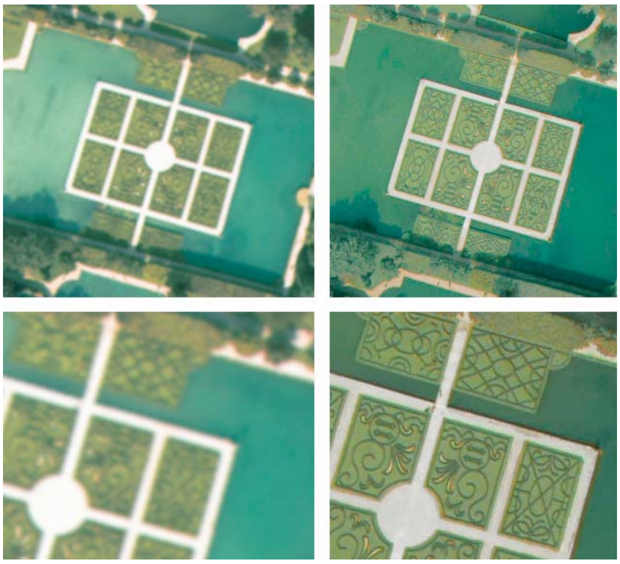


Figure 7: Example of two color images. Left is a digital color image with (above) 935 x 719 pixels, each pixel with 55 cm, using a Bayer pattern, and (below) a segment enlarged from that larger segment. To the right is a colorized panchromatic aerial image with pixels at 17 cm. Color pixels are thus 3 times as large as panchromatic pixels and are used for “pan-sharpening” or coloration.

3.1.4 Wavelet Concept:
A high resolution PAN image is decomposed into a set of low resolution panchromatic images with wavelet coefficients for each level. Then low resolution panchromatic images are being

replaced with a multi-spectral band at the same resolution level, and a reverse wavelet transform is being performed for each of the three RGB-layers.

3.3 Effect of Different Color Input Resolutions on the Output Image Resolution

It is of interest to compare digital color images that have been obtained by coloration, but using different geometric resolutions for the color components. We present in Figure 7 an example of two color images at different pixel sizes in color (55 cm) and black & white (17 cm). The pan-sharpened color image far exceeds the detail available from the color image itself. The area is in Salzburg, Austria.

Figure 8: Detail from a scanned aerial photograph of downtown Salzburg, Austria. Pixel size on the ground is about 25 cm in the scanned original. From the source image, a reduced color version has been computed and submitted to a coloration procedure. Left: this image has color pixels that are 5 times as large as panchromatic pixels, and the combination is being shown. Right: The full resolution color image does not show differences.

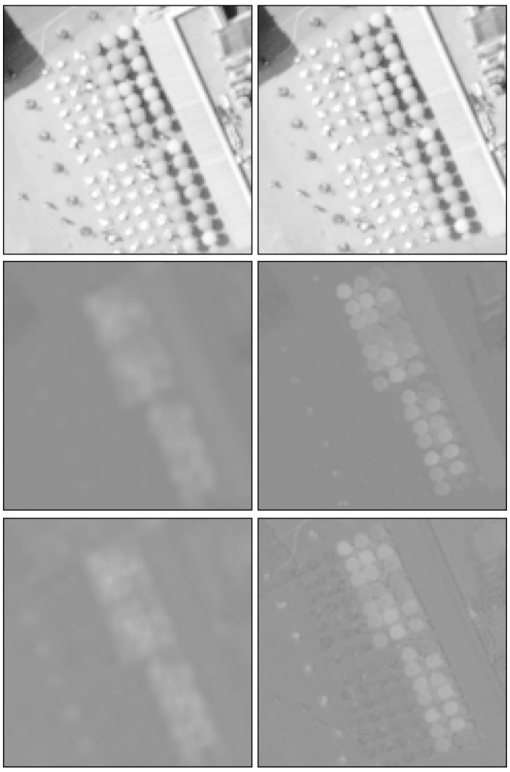


Figure 9: Presenting the three LAB components for the two color images in Figure 8. Luminosity (above), a-channel (middle) , b-channel (below). The “a” and “b” color components show differences in geometric resolution, whereas the colorized images in Fig. 8 do not.

Figure 8 is another example that in this case results from a simulation using scanned aerial color photography. The pixels at about 25 cm on the ground are separated into a luminosity and two color channels in the LAB color model, and the color pixel’s resolution was changed by a factor of 5. Figure 8 shows the resulting color images with reduced and full color resolution (left is reduced, right is full resolution). Figure 9 presents the LAB-component images for the two versions.

Figure 10: Low resolution of chromatic channels at 1/8 of the resolution of the luminosity causes a visible reduction of the color and image quality. The upper row shows the rgb-representation of the image segment, the lower row shows the red color channel.. To the left is the reduced version, to the right the full resolution image. Note the “bleeding” of the red of the car into the surrounding parking lot.

4 DEMOSAICKING THE BAYER PATTERN

4.1 Demosaicking Alternatives

The Bayer pattern assigns to each pixel only one color value, when a color image needs three such values at each pixel location. Demosaicking is the process by which each input pixel location will obtain two additional color values using the surrounding values at other pixels. Figure 11 shows the result of applying these various procedures to the simulated example in Figure 5. Demosaicking will remove most of the so-called “zipper-effect” which describes the color fringes along edges.

In Figure 11, various demosaicking results are illustrated, as obtained by a variety of procedures, namely:

(a) shows the nearest neighbor interpolation where the neighboring color value gets replicated;
(b) bilinear interpolation is shown using the 4 neighboring pixels;.
(c) constant hue-based interpolation by Cok (1986, 1987), interpolating bilinearly for the green channel. Red and blue channels are interpolated so that a smooth transition in hue from pixel to pixel is achieved;
(d) is the same as (c), with the difference that the values are mapped onto logarithmic exposure space;
(e) gradient-based interpolation by Hibbard (1995), with the interpolation considering the gradients in horizontal and vertical directions, to avoid the "zipper effect";

(f) the same method as in (e), but with a different computation of the gradients, Laroche and Prescott (1994);
(g) adaptive color plan interpolation Hamilton and Adams (1997), interpolating using also the 2nd derivative to avoid the "zipper effect" at edges;
h) variable number of gradients interpolation by Chang et al. (1999). Interpolation uses the derivatives in 8 directions within a 5x5 window;

Overviews of this topic are found in Adams (1995). A very different approach was suggested by Nayar and Narasimhan (2002) using learned structural models for the reconstruction.

Root mean square errors of results in Figure 11 are given in Table 1.

Demosaicking Case	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
RMSE	10.6	5.8	4.2	4.4	4.9	3.4	2.7	2.4

Table 1: Differences between the original true color value at a pixel and its reconstructed value in DN. The smallest errors occur in methods (g) with adaptive color interpolation and in method (h).

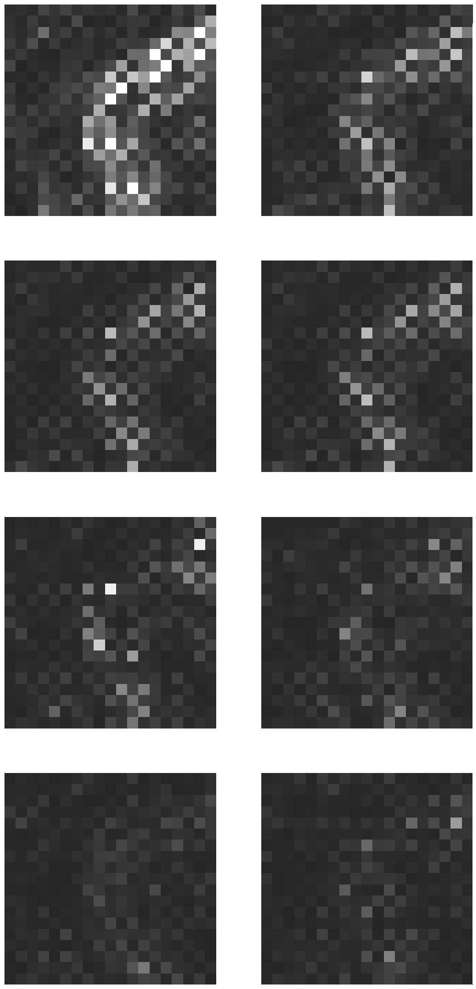
(a), (b)

(c), (d)

(e) (f)

(g), (h)

Figure 11: Demosaicking using 8 different methods (a) to (h) presented in the text and described in the literature. This is being illustrated by 19 x 19 pixels taken from the simulation in Figure 5. Colors are bleeding in various ways, depending on the method used for coloration. The best result can be assessed mathematically and is method (h).



(a), (b)

(c), (d)

(e) (f)

(g), (h)

Figure 12: Demosaicking errors of the simulated results, obtained by comparing the demosaicked image segments of Figure 11 with the input color image in Figure 5, showing a 19 x 19 pixel window.

The demosaicked image segments of Figure 11 do not show the differences between the demosaicked image and the source in Figure 5. That difference can be obtained by subtracting the demosaicked image from the input, using the luminance value. The result is shown in Figure 12 and is an image of the differences. The rmse-values were already presented in Table 1.

5 CONCLUSION

We have presented various alternatives for the creation of digital color images from an aerial or space sensor. We have also explained the issue of “pan-sharpened” images using higher resolution panchromatic images and lower resolution color images. An experiment is described to classify the errors committed in demosaicking so-called Bayer pattern color images. The adaptive color interpolation using second derivatives and the variable number of gradients method produce the smallest errors in the range of ± 2 DN-values.

REFERENCES

Adams J. jr. (1995) *Interactions between color plane interpolation and other image processing functions in electronic photography*. Electronic Imaging, Proc. SPIE, 2416:144–155.

Adams, J. (1997) *Design Of Practical Color Filter Array Interpolation Algorithms For Digital Cameras*, Proc. of SPIE, vol. 3028, pp.117-125.

Bayer B. E. (1976) Color Imaging Array. US Patent 3,971,065.

Chang E., Shifun Cheung, and Davis Pan (1999). *Color filter array recovery using a threshold-based variable number of gradients*. Proceedings of SPIE (San Jose, CA), 3650:3643, January.

Cok D.R. (1986) *Signal processing method and apparatus for sampled image signals*. U.S. Patent 4,630,307.

Cok D.R. (1987) *Signal processing method and apparatus for producing interpolated chrominance values in a sampled color image signal*. U.S. Patent 4,642,678.

Emerge (2002) *Introducing the Emerge Digital Sensor System*. http://www.emergeweb.com/

Enerquest Inc. (2002*) 4K by 4K Digital Camera Now Available from Enerquest*. http://www.enerquest.com.

Hamilton H. and J.E. Adams (1997) *Adaptive color plan interpolation in single sensor color electronic camera*. U.S. Patent 5,629,734.

Hibbard R.H. (1995) *Apparatus and method for adaptively interpolating a full color image utilizing luminance gradients*. U.S. Patent 5,382,976.

Laroche C.A. and M.A. Prescott (1994). *Apparatus and method for adaptively interpolating a full color image utilizing chrominance gradients*. U.S. Patent 5,373,322.

Leica (2002) *ADS40 Airborne Digital Sensor – Photogrammetry Goes Totally Digital*. http://gis.leica-geosystems.com /products/ads40.html.

Nayar Shree K. and Srinivasa G. Narasimhan (2002) *Assorted pixels: Multi-sampled imaging with structural models*. ECCV, LNCS 2353:636–652, May.

Positive Systems (2001) *ADAR Systems Overview*. http://www.possys.com/adar.html

Zhang Y. (2002) *Automatic image fusion - A new sharpening technique for IKONOS multi spectral images*. GIM International, pages 54–57, May.

Z/I Inc (2002) *Digital Mapping Camera*. http://www.ziimaging.com/Products /AerialCameraSystems/DMC.htm