Considerations for Bayer filter digital cameras

Users of single chip color digital cameras have lots of choices in camera features. The following are a few issues relating to these types of cameras that users need to be aware of when they are choosing their camera type.

What is a Bayer Filter?

A Bayer Filter color camera is a single chip color camera that has a color sensitive filter placed over the top of the sensor. Bayer filters are also often referred to as Bayer Mosaic or a Primary color filters. These color filters have alternating cells sensitive to a particular color with the typical breakdown of color sensitive array elements is ¼ red, ¼ blue, and ½ green. These filters have more green sensitive pixels than red or blue to better mimic the human eye's greater sensitivity in the green and to increase the contrast resolving power of these sensors. You may also find some filters referred to as Complementary Color Filters, where filter element are sensitive to Cyan, Magenta, Green and some with Yellow. Complementary color filters tend to be more sensitive than Bayer filters, but these will be covered in another upcoming paper.

	0	1	2	3	..		
0	G	B	G	B		G	B
1	R	G	R	G		R	G
2	G	B	G	B		G	B
3	R	G	R	G		R	G
..							
	G	B	G	B		G	B
	R	G	R	G		R	G

How do you get a color image from a Bayer filter camera?

The 3 following steps must occur for a single chip color camera to output a viewable color image. Where each of these steps is performed and how they are performed may vary from camera to camera.

1) Light is acquired into individual pixels thru the Bayer filter and is quantified as an intensity value relative to each pixel in the sensor. The individual Bayer Filters only allow light of that color to transmit thru and to be acquired.

G	B	G	B	...
R	G	R	G	
G	B	G	B	
R	G	R	G	
⋮				

2) The acquired image is now just an array of relative intensity values. Pixel 0,0 has an intensity of 230 relative to Green. 1,0 has an intensity of 48 relative to Blue, etc. This data is NOT a viewable color image. Bayer conversion or interpolation must be performed to make the intensity data into a viewable color image.

230	48	193	91	...
121	213	147	152	
47	96	188	56	
199	165	239	31	
⋮				

3) Bayer conversion/interpolation must be performed on the above intensity values to generate a viewable color image. Intensity values from adjacent pixels are interpolated to generate adjacent color values. The resulting

R	R	R	R	...
R	R	R	R	
R	R	R	R	
R	R	R	R	
⋮				

G	G	G	G	...
G	G	G	G	
G	G	G	G	
G	G	G	G	
⋮				

B	B	B	B	...
B	B	B	B	
B	B	B	B	
B	B	B	B	
⋮				

viewable color image will typically increase in size 2-3 times depending upon the output image format.

Where is Bayer conversion performed?
Fine question. This is something that varies from camera to camera. Steps 1 and 2 above are always performed in the camera. Step 3 can be performed in the camera or in the host computer. If Bayer conversion is performed in the camera, the resulting amount of data output by the camera increases ~2-3 times over un-interpolated/raw Bayer data. If Bayer conversion is performed by the computer, the CPU has to perform quite a bit more work.

Bayer conversion is CPU intensive and the better algorithms (less color artifacts in the resulting image) take more CPU processing. For many applications this use of the CPU isn't important, but for others, the CPU is needed to perform processing on the color images and this may be a factor. More sophisticated digital color cameras can perform the color interpolation in the camera hardware and can output some form of color images, but these images will be larger than the raw Bayer image data, and this increase in data may affect the number of frames/second that the camera can output in this mode. Also, cameras performing the interpolation inside the camera need dedicated hardware to perform this processing. This is typically done in a gate array. The more sophisticated the algorithm, the larger the gate array. The larger the gate array, the higher the camera cost. Users needing more than a basic Bayer conversion algorithm in the camera need to be sure that what is implemented in the camera will provide satisfactory results for their imagery and if not, that their specific algorithm can be added to the camera and at what cost. Otherwise, the Bayer conversion needs to be done in the host computer.

Users looking for a digital color camera need to be sure they understand the capabilities of their camera choices to match their requirements for frames/second and how much work the CPU is allowed to perform within the requirements of their particular application.

Why don't all digital cameras give me RGB data?
Bandwidth. RGB images are ~3 times as large as raw Bayer image data. The tradeoff between RGB and raw Bayer data outputs may results in a difference in the camera's maximum frame rate as outputting RGB significantly increases the amount of data the camera must output, resulting in exceeding the camera's output type. An example may help explain this:

A single chip color camera with a resolution of 1024x1024 outputs 8 bit raw Bayer data at 30 frames/second. Each image out of the camera is 1Megabyte and the camera is outputting 30X this or 30Mbytes/second. 30Mbytes/second is at the top end of what a camera with a IEEE1394A or a USB2.0 output can sustain. A similar camera, where the camera performs the Bayer interpolation and outputs RGB, is now outputting 3X, or 90Mbytes/second of data, far exceeding what IEEE1394A or USB2.0 can sustain. For customers who want to achieve more frames per second, raw Bayer output may be the only way to achieve this.

Color Formats

Bayer conversion can generate results in different color formats. The choice of what color format your Bayer image is converted into also has some affect on bandwidth and usability for a particular application. Here is a sampling and some of their tradeoffs:

- Raw X – In this mode the camera will output raw, un-interpolated Bayer data out of the camera. The X represents the bit depth that the interpolation algorithm is outputting the image data as, typically 8. In this format the camera should be able to achieve the highest frame rate as the amount of data being output is the smallest compared to the interpolated formats:
- RGB – a non sub-sampled format where each pixel in the image will have a red, blue and green component to it. This will almost always provide the highest color fidelity, but typically the most data … typically 3 times the Raw format
- For YUV (often referred to as YCrCb) formats, a color is represented by a luminance (Y = intensity/brightness) and 2 chrominance (U=Cb=component blue, V=Cr=component Red) values. YUV formats are much more designed for color analysis than RGB formats. YUV formats take advantage of the fact that human vision is more response to luminance than chrominance and that humans typically can't tell the difference between RGB and the lower bandwidth YUV411 (50% less data than RGB) and the YUV422 (33% less data than RGB) formats. A note is that in YUV formats the 4:4:4, 4:2:2, 4:1:1 denote the relative size of each component, and not the absolute size. A YUV 4:4:4 color value is not 4 bits of Red, Green and Blue, but is equal parts of Red, Green and Blue
  - o YUV 4:4:4 has equal parts luminance and both chrominance values and has the same bandwidth as an RGB image
  - o YUV 4:2:2 Two chrominance components are sampled at half the sample rate of luminance, so horizontal chrominance resolution is cut in half. This reduces the bandwidth of the digital image by one-third with little to no visual difference. If the raw data is 8 bit, the image data is represented by 8 bytes for every 4 pixels in the image with 4 Y's and 2 each U and V. Effectively twice the raw image format
  - o YUV 4:1:1 In 4:1:1 chrominance sub-sampling, the horizontal color resolution is quartered. The bandwidth is halved compared to no chrominance sub-sampling (YUV 4:4:4). A color pixel is transmitted at 12 bits/pixel or 6 bytes for every 4 pixels in the image

Conculsion
There are many tradeoffs when selecting digital color cameras that a user must be aware of including bandwidth and CPU load when performing Bayer conversion. For cameras with on-board color conversion, use of this feature may lower the camera's maximum frame rate to stay within the limits of the camera's output type. CPU Bayer conversion will certainly increase the load on the computers processor. The Bayer conversion, whether performed on-board the camera or in the CPU, will generate color viewable images, but the Bayer conversion algorithm used may not generate images with a type or a quality which can be used for quantitative image processing.

About the author: Ron Bryan is a sales engineer with 1st Vision, Inc. and has worked for many image processing and machine vision pioneers during the last 20 years. He has a BS Computer Science from UC Riverside.