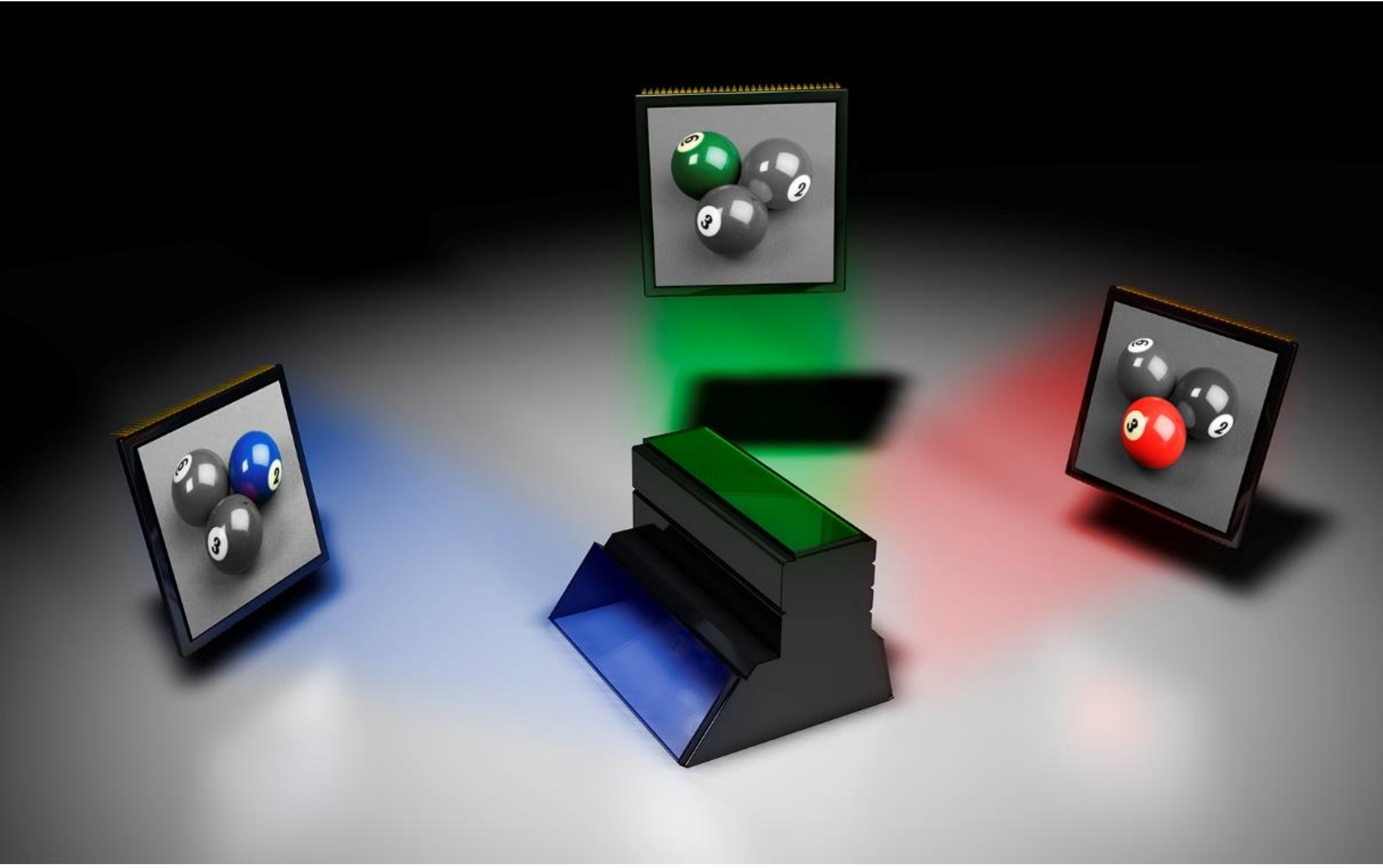

WHITE PAPER

# How does prism technology help to achieve superior color image quality?

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# How does prism technology help to achieve superior color image quality?


*Abstract*

*Achieving superior image quality requires real and full color depth for every channel, improved color contrast and color differentiation, low inter-channel crosstalk and noise levels. These vital image quality factors can be achieved using the unique advantages of prism technology. Cameras based on Bayer pattern sensors block part of the light falling on it due to the very nature of the light filtering process. Due to this reason, several camera technologies on the market rely heavily on FPGA based image processing to repair image quality. On the other hand, prism-based cameras separate the incoming light in an innovative way that avoids loss of signal intensity. Furthermore, prism technology proves that in order to achieve superior image quality, what matters most is the way light is captured onto image sensors.*


## 1 Background and Motivation

Since the advent of machine vision, camera technology has been at the center of its growth. Image sensors used in these cameras have developed exponentially. A few of the CMOS sensors available today (like the 2nd generation Sony IMX Pregius Series) provide better SNR, stability and linearity than some CCD sensors. Today, even though a large portion of imaging is monochrome, the share of color cameras is growing much faster than expected. A large part of color imaging is based on “Bayer pattern sensors”. As there is no significant pricing difference between monochrome and Bayer sensors, the latter has been successful in replacing monochrome cameras in many low cost applications where color requirements are fairly simple. Camera manufacturers are able to take full advantage of these developments and today it has become relatively easy to assemble these sensors in simple camera housing, then add signal processing and a data interface to it. As the market demand for superior color image quality is growing, there has been a significant effort to add intelligent image processing algorithms on the camera head to repair the artifacts arising from the Bayer pattern. However, this improvement is at the cost of critical factors such as sharpness, color accuracy, image noise and speed.

On the other hand, multi-sensor prism-based cameras are sophisticated. The assembly of sensors along with the prism block requires very high precision and demands in-depth know-how and skill. The advantage of this technology is superior image quality which does not require image repair. This white paper focuses on multi-sensor prism-based camera technology, highlights its technological advantages and showcases the future of color imaging in machine vision.

# 2 Multi-sensor prism-based vs. single sensor cameras

## 2.1 Propagation of light

Inside a prism-based camera, the photons entering the optical system propagate through the prism before interacting with the sensors.

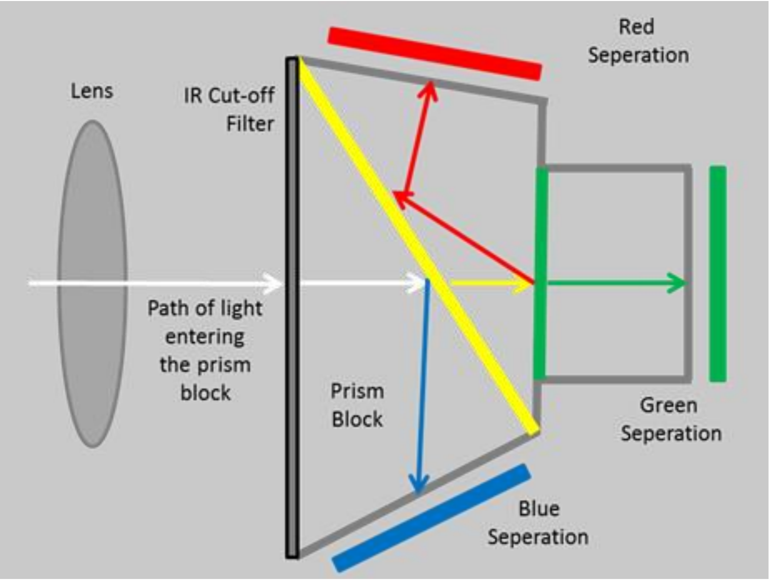


*Fig. 1 - Separation of light inside the prism block*

The prism block consists of multiple prisms which are equipped with hard dichroic coatings to assist in the separation of light. Fig. 1 shows the separation of white light inside the prism block. The short wavelength, i.e., blue region of the spectrum, is separated first, followed by red while the green passes through the prism. Light is separated before interacting with the sensor. This approach ensures minimum loss of signal strength. As wavelength and frequency are inversely proportional, the prism design is optimized to allow a shorter propagation distance for the blue component than the red. In the case of RGB cameras, an infrared cut off filter on the top of the prism block separates the visible and IR component. It also supports in avoiding artifacts in the blue and green channel.

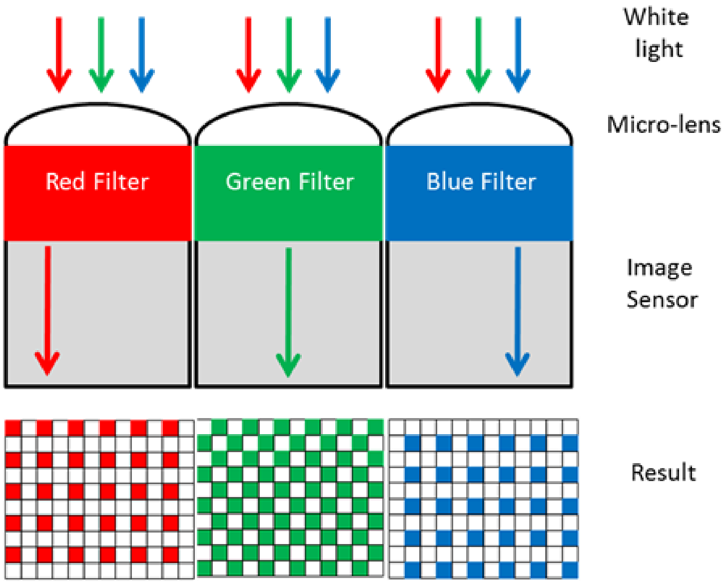


*Fig. 2 - Filtering of light on a Bayer sensor*

In the case of a single sensor Bayer RGB camera, the white light propagates through the Bayer pattern. Depending on the color of the filter that overlays a given pixel, only the portion of the incoming light within that spectral band will reach the photodiodes and generate a signal value for that pixel.

### 2.2 True color vs. estimated color

True color accuracy comes naturally to prism cameras due to their optical construction. Multi-sensor prism based cameras consist of one image sensor per color separation (3 monochrome sensors in the case of RGB, 4 monochrome sensors in the case of RGB + NIR). Every pixel captures true color information in full bit depth. True color forms the basis for better color differentiation, avoiding false color representation, reducing metamerism and providing better image contrast.

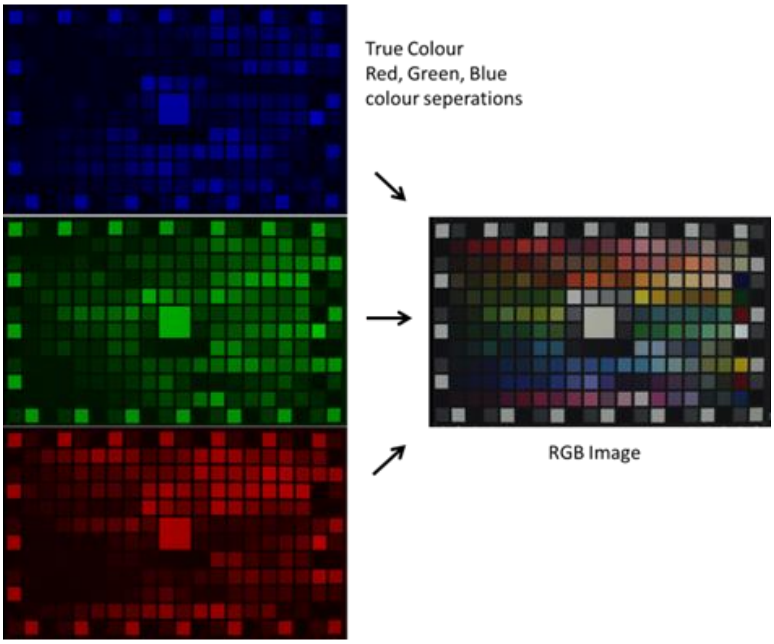


*Fig. 3 – True color imaging with multi-sensor prism cameras*

On the other hand, Bayer RGB cameras consist of a mosaic pattern. Normally the number of green pixels is double that of red and blue to mimic the visual perception of the human eye. Since each pixel is assigned to record only one of the three colors, the output from each pixel cannot fully specify the missing red, green and blue information on its own.

Hence, full color information is only possible by using debayering algorithms which interpolate the missing information from neighboring pixels and provide estimation. As this process involves image processing, cameras need larger FPGA capacities if the debayering matrix exceeds 3x3 or a 5x5 constellation. The 5x5 debayering process does show small improvement on edges and image artifacts.

However, the debayering process often leads to false representation of image quality. There is no guarantee of producing good results which reflects the basic nature of estimation algorithms. Additionally, there is a tradeoff between speed and quality of interpolation.

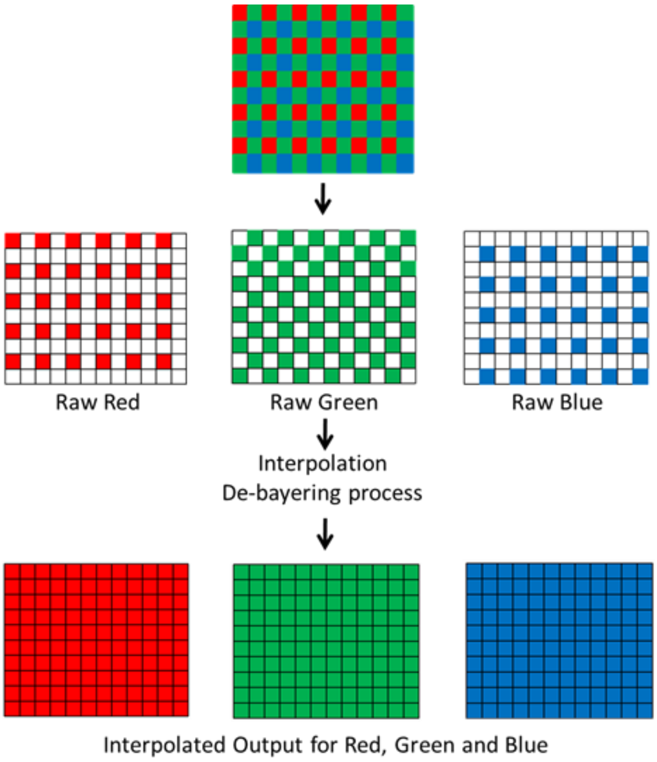


*Fig. 4 – Estimated color output using Bayer RGB*

## 2.3 Spectral separation and color crosstalk

The color filter array (CFA) for Bayer RGB and several other color sensors like tri-linear are made up of color dyes or pigments. Due to the very nature of these materials, the spectral distribution for blue extends into green and red, green extends into blue and red and red extends into green. For most of the machine vision applications which demand better spectral differentiation, the result of this extension is contamination due to unwanted signal. In addition to CFA, the very nature of CMOS sensors leads to color crosstalk when photons falling on one pixel are falsely sensed by the pixels around it. The effect of color crosstalk could be further visible during the debayering process where the false pixel values are used for interpolation.

As the sensor resolution is constantly increasing, compensating for crosstalk is extremely challenging, especially for small pixels with CFA. Fig. 5 shows color crosstalk of a typical Bayer pattern sensor. It is evident that this crosstalk leads to poor spectral differentiation as a signal in the blue region is also detected by green and red. Similarly, green is detected in blue and red and red is detected in blue and green.

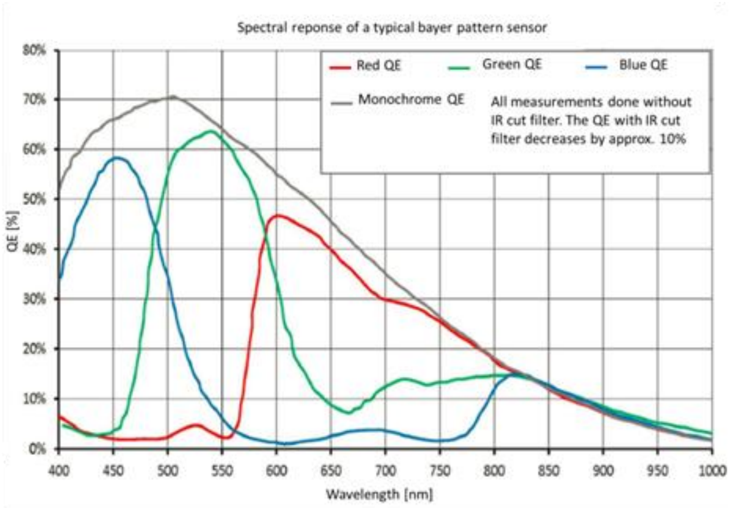


*Fig. 5 – Spectral separation of a Bayer pattern RGB sensor*

On the other hand, multi-sensor prism-based cameras offer better spectral differentiation which is a result of low color crosstalk. This is depicted in Fig. 6.

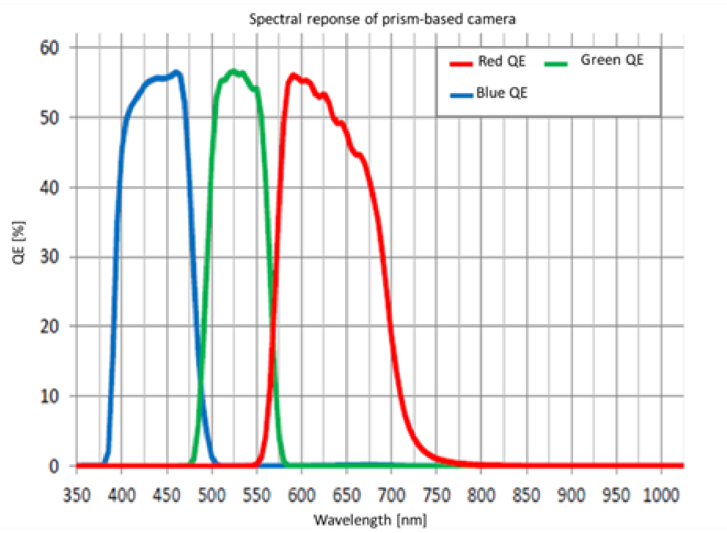


*Fig. 6 – Spectral separation of a prism-based camera with IR-cut filter*

The dichroic interference filters are steep in nature and provide more efficient filtering than pigment or dye-based ones. The life time of these filters is much longer because the color is intrinsic in the construction of hard microscopic layers. Unlike Bayer RGB cameras where the sensor response could describe the camera response, prism-based cameras are different. The spectral response is not only a function of the sensor but also the transmission of light through the prism.

As this is an example of an RGB camera, an IR cut filter is included. Furthermore, the transmission properties and coating characteristics of the prism can be varied depending on the need of different applications, e.g., the spectral properties of prisms in some cameras are optimized to facilitate for a better white balance.

### 2.4 Exposure and gain control

In camera technology, gain is the amplification of signal. Fig. 7 explains a typical situation with single sensor Bayer RGB cameras. It depicts an imaging setup where the green channel has reached maximum signal strength required to achieve white balance. Signal strength very much varies with the wavelength of the light. The typical green dominance could arise from an illumination which is stronger in the green region of the spectrum. This leads to a deficit in signal levels for blue and red. The only way to achieve similar signal as green is to amplify the remaining two channels. The digital/analog gain amplifies the complete signal including the noise. As single sensor cameras have a common exposure time for all channels, there is no possibility to optimize channel dependent noise.

In contrast to this, a prism based, multi-sensor camera has every color channel equipped with a separate sensor. Analog gain can thus be optimized independently for every single color channel. Furthermore, multi-sensor cameras also allow adjusting exposure times for each sensor, separately. Each color channel can thus be optimally adjusted in gain and exposure time to achieve optimal signal to noise ratio for every color channel.

SNR in a bright scene is dominated by shot noise which is defined by the square root of the number of electrons. This means that the noise is directly proportional to camera gain.

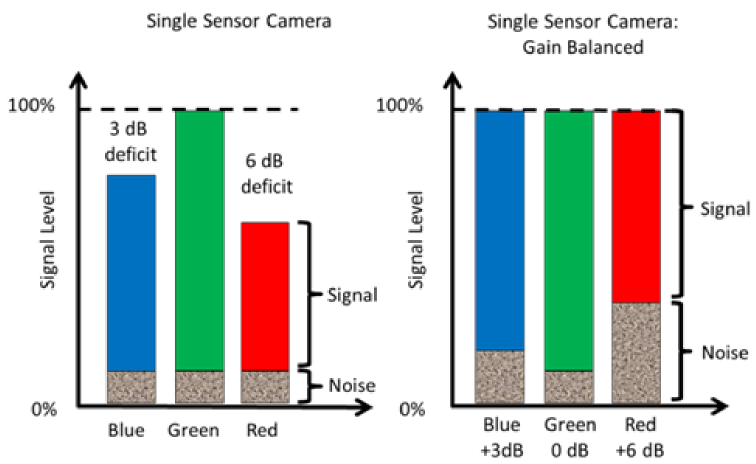


***Fig. 7 – Grey level balancing with digital/analog gain in single sensor cameras***

However, optimizing individual exposure before gain shows better SNR than using common exposure. Multi-sensor prism-based cameras consist of both features to achieve superior image quality. This is depicted in Fig. 8.

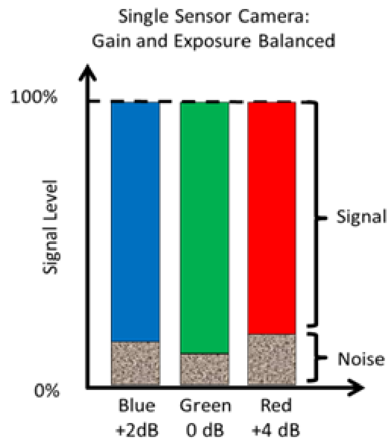


*Fig. 8 – Optimizing grey levels with digital/analog gain and exposure time in multi-sensor prism cameras*

## 2.5 Resolution

In machine vision, resolution is often measured in number of pixels a camera is offering. In color cameras, this number could be misleading as single-sensor Bayer pattern color cameras interpolate the image information in every pixel out of a 2x2 pixel (or more) matrix. This paper differentiates resolution in terms of spatial resolution and field-of-view (FOV).

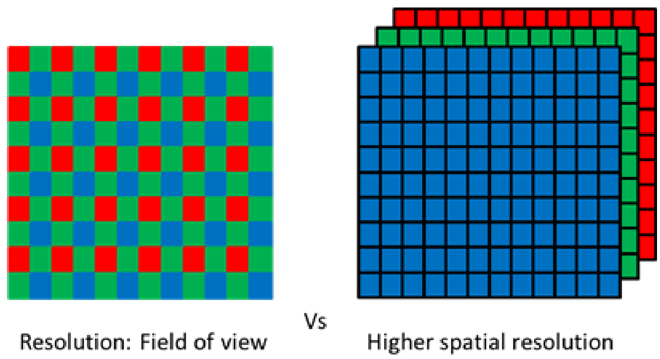


*Fig. 9 - Bayer RGB vs multi-sensor camera resolution*

Assuming the use of lenses with same focal length, the FOV of a camera depends on the size of its sensor which is directly proportional to the number of pixels. A camera with a high pixel count can therefore cover a wider FOV.

On the other hand, spatial resolution is driven by pixel size. The smaller the pixel, the higher is the resolution. As pointed out above, in Bayer pattern cameras the matrix used for debayering has to be taken into account while determining the pixel size and calculating the resolution. For a typical 2x2 Bayer-pattern sensor, spatial resolution decreases by a



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factor of 4 for the blue and red and by a factor of 2 for the green channel.

Due to size of the prism, multi-sensor cameras are limited in the size of its sensors and thus typically come with smaller pixel counts. Their FOV is often smaller than the one of Bayer-pattern cameras. Yet despite their lower pixel count, spatial resolution is higher than in Bayer pattern cameras with same pixel sizes. Thanks to their multi-sensor prism design, one sensor per color channel is available to cover the same FOV. Hence, every color channel is imaged with full pixel resolution of the sensor.

Table 1 below shows a comparison between the JAI AP-3200C-USB prism camera to a Bayer-pattern IMX 265 (3.2 MP) and IMX 253 (12.3 MP). The JAI AP-3200T-USB is equipped with three 3.2 MP Sony IMX-265 monochrome sensors.

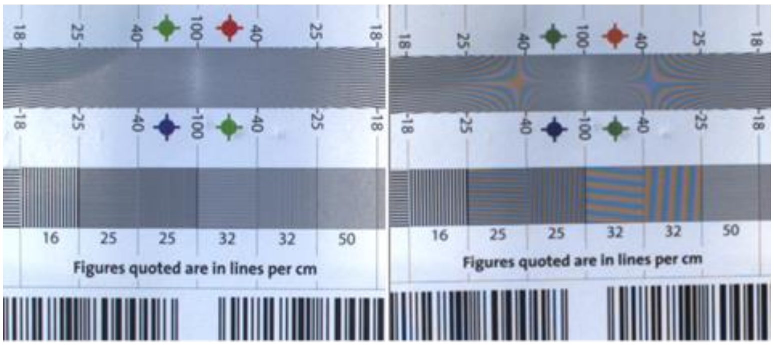
The numbers show that FOV obviously increases with pixel count. However, this is not the case for spatial resolution. Despite the much higher pixel count of the IMX-253 sensor, spatial resolution is the same as with cameras equipped with a much smaller IMX-265 Bayer pattern sensor. In both cameras, resolution depends on the color channel with resolution in the green being higher than resolution in the blue and red channels.

In contrast, the AP-3200T prism camera shows average three-times higher spatial resolution compared to the Bayer pattern cameras. This holds true also in when compared to the IMX-253 Bayer pattern camera which offers a higher pixel count than the total 3x3.2 MP count of the prism based camera.

| | AP-3200T Prism-based camera | IMX-265 Bayer pattern camera | IMX-253 Bayer pattern camera |
|---|---|---|---|
| Pixel count | 3 x 3.2MP | 3.2MP | 12.3 MP |
| FOV | 2048 x 1536 (x 3.45µm) | 2048 x 1536 (x 3.45µm) | 4096 x 3000 (x 3.45µm) |
| Spatial Resolution | 3.45µm | Green: 6.9µm<br>Blue/Red: 13.8µm | Green: 6.9µm<br>Blue/Red: 13.8µm |

***Table 1 - Comparison of FOV and spatial resolution of prism based and Bayer-pattern based cameras of different pixel counts. All cameras are with sensors featuring the 3.45 µm pixel size. FOV and Spatial Resolution values assume a lens with a 1:1 projection of object size onto image size on the sensor.***

The outlined differences become visible in color images taken of spatial black and white test charts (Fig. 10). While images taken with a Bayer-pattern camera show blue and red interference (moiré) patterns (these are the colors with the lowest resolution), such artifacts are not visible in images taken with multi-sensor cameras.




AP-3200T (multi-sensor prism-based)    Single sensor (IMX264) camera

*Fig. 10 – Prism vs. Bayer image (moiré patterns)*

Multi-sensor, prism based cameras are thus clearly superior in applications depending on a good spatial resolution such as print inspection or microscopy.

## 3 Image quality

For designers of color machine vision systems, the net result of all of these differences is better overall results from prism cameras for applications where image quality is paramount.



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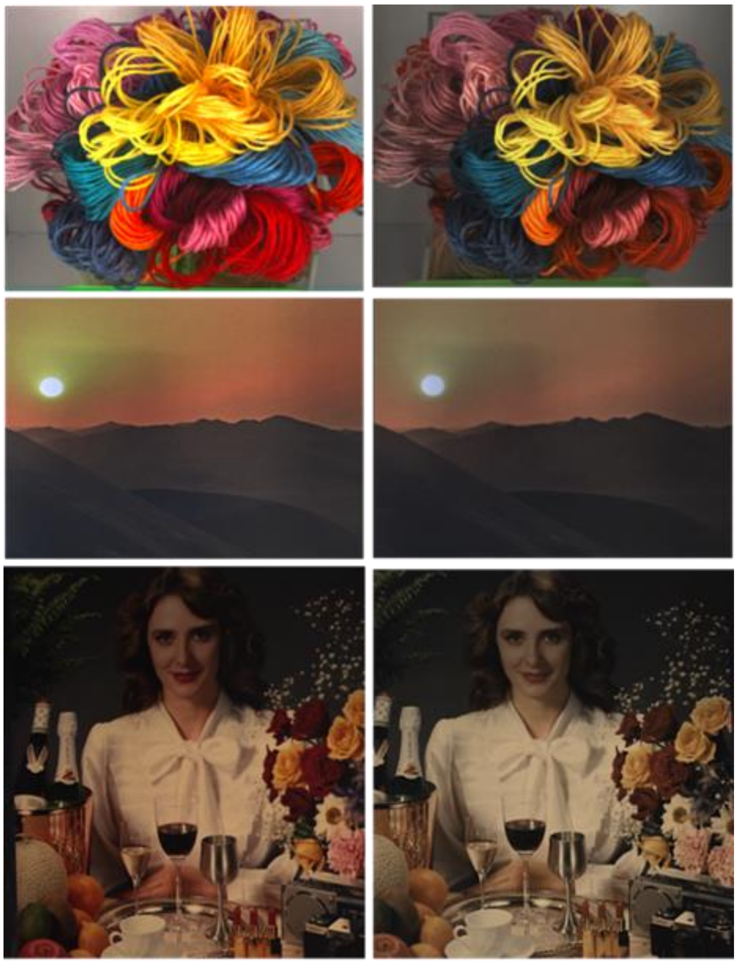


*Fig. 11 – Image comparison of RGB multi-sensor prism-based camera and single sensor Bayer RGB camera*

The images in Fig. 11 are captured with a JAI AP-3200T-USB prism camera (left column) and a JAI GO-5100C-USB Bayer camera (right column). The superior image quality in terms of better color differentiation, vibrant hues, better contrast and good image depth is clearly visible in the left column images.

## 4 Other parameters for getting the best out of multi-sensor prism cameras

### 4.1 Selecting the right lens

Even though some of the standard machine vision lenses work well, special lenses are available to get the best image quality out of prism-based cameras. Multi-sensor cameras employ a prism which puts additional constraints on the lens design. Apart from the optical path being longer through the prism onto the sensors, the lens must fit well on the sensor format. If the image circle of the lens is smaller than the sensor, color shading would be a visible consequence. The visibility of the shading effect increases in prism cameras due to the dichroic coatings on the prism. It leads to difficulties in achieving the correct white balance. Lenses designed for multi-sensor prism cameras also have a larger exit pupil resulting in a smaller angle of light rays passing through the dichroic prism. Furthermore, they do not deteriorate drastically in MTF (modular transfer function) along the edges.

There are several manufacturers of lenses for prism-based cameras on the market such as VS Technology, Kowa, Fujinon, Myutron, Goyo Optical, Azure and Blue Vision.

### 4.2 On-camera features

As the leading provider of prism color cameras, JAI offers several additional functions on its prism cameras to further enhance image information according to the requirements of various applications. For example, color conversion algorithms help to convert normal RGB output into other three dimensional color spaces such as sRGB, Adobe RGB, HSI and CIEXYZ. The effects of a prism camera's superior image quality are also visible in the quality of these conversions. A color conversion based on Bayer RGB would be less precise than a conversion based on an RGB prism-based camera. Similar logic of precision in conversion applies to converting camera RGB into custom RGB based on color temperature presets and application specific look-up tables. Enhancer functions for colors and edges, pixel binning, shading correction based on ROI, automatic gain and shutter control, single and multi-ROI functions, and chunk data for each image are some of the additional features which could be used for getting the best out of prism-based cameras.

## 5 Conclusion and outlook

The advantages of prism-based cameras over single sensor RGB Bayer cameras for machine vision applications are outlined in this paper. Furthermore, the advantages are aligned with parameters responsible for achieving superior image quality such as true color, high spatial resolution, lower spectral crosstalk and SNR, better contrast and color differentiation. The paper highlights the fact that no matter what degree of on-board image processing is used to repair Bayer RGB images, what matters is how the light signals are recorded onto the image sensor.

This paper covers the basics of prism technology for multi-sensor area scan cameras and is a part of a white paper series on prism technology. Apart from covering the fundamentals, the aim of this series is to share knowledge on applications, metrology and how to use camera functionalities to extract the best out of multi-sensor prism based cameras.

## About the authors

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Paritosh is a part of JAI product management team since April 2017. He studied print and media technology at Chemnitz University of Technology in Germany and specialized in multi-spectral camera systems for high speed applications. Having worked in previous positions within R&D for paper technology, camera development, application management for 3D & spectral cameras and sales he brings a broad perspective to the table.

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Yizhe joined the JAI product management team in August 2017. He studied Law at the Shanghai Institute of Foreign Trade and Commerce and later at the Waseda University in Japan and specialized in International Commerce and Law. He has worked extensively in sales of surveillance lenses with responsibility of Chinese and Japanese markets and later in product planning and global marketing for surveillance cameras.

Shuichi Shibui

Director, Global Marketing
Product Management

Shuichi joined JAI in 2015. With over 20 years of experience in image sensors and semiconductors, he has held various positions with leading semiconductor and image sensor manufacturers. After getting a degree in electronics from Tokai University in Japan, Shuichi was responsible for launching several key image sensors in the market.

## About JAI

JAI provides innovative digital CCD/CMOS camera technology for applications in industrial machine vision, medical imaging and high-end surveillance systems, as well as complete solutions for traffic imaging/vehicle recognition in Intelligent Traffic Systems (ITS). The company has a global presence through companies in Denmark, Germany, Japan, China and USA, and via distribution partners in more than 35 countries.

JAI's vision systems help improve customer businesses in numerous ways, whether by improving quality and accuracy of products, lowering production line inspection costs, increasing production yields or creating higher efficiency in road traffic. Common to our customers around the globe is that they value the trademark characteristics of our products: proven technology, high reliability, consistent quality and superior image fidelity backed by JAI's long-term viability.

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