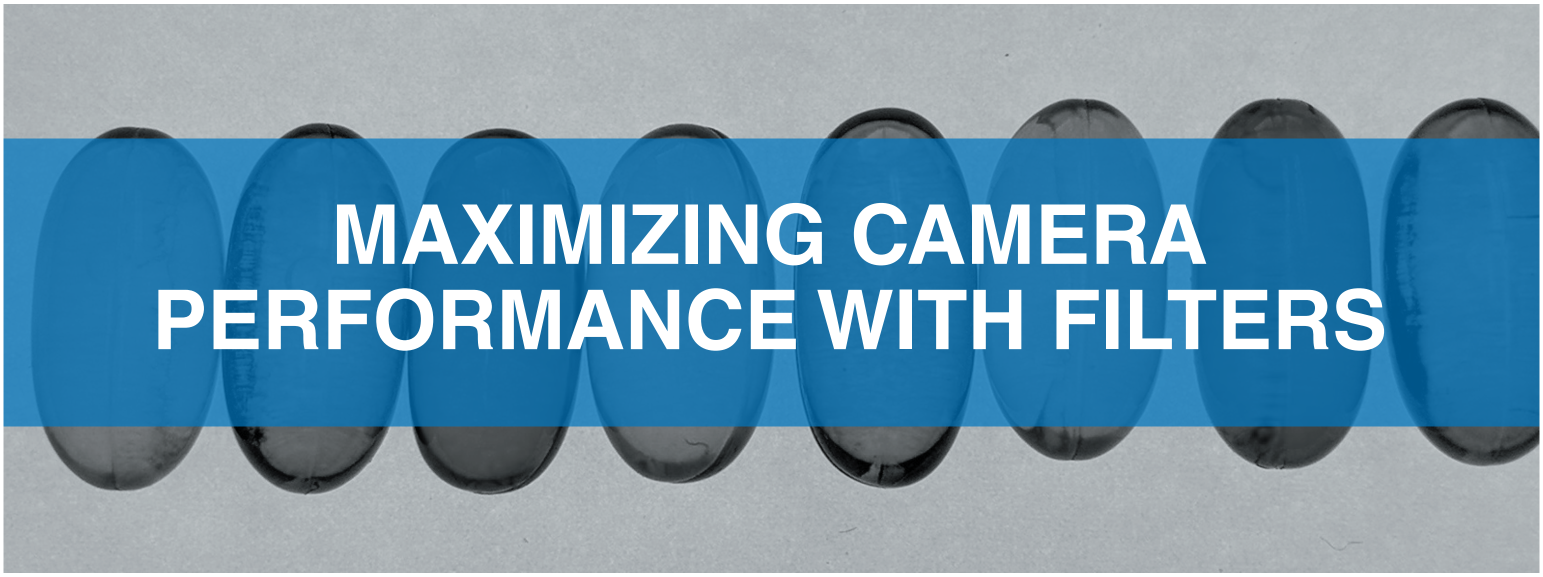
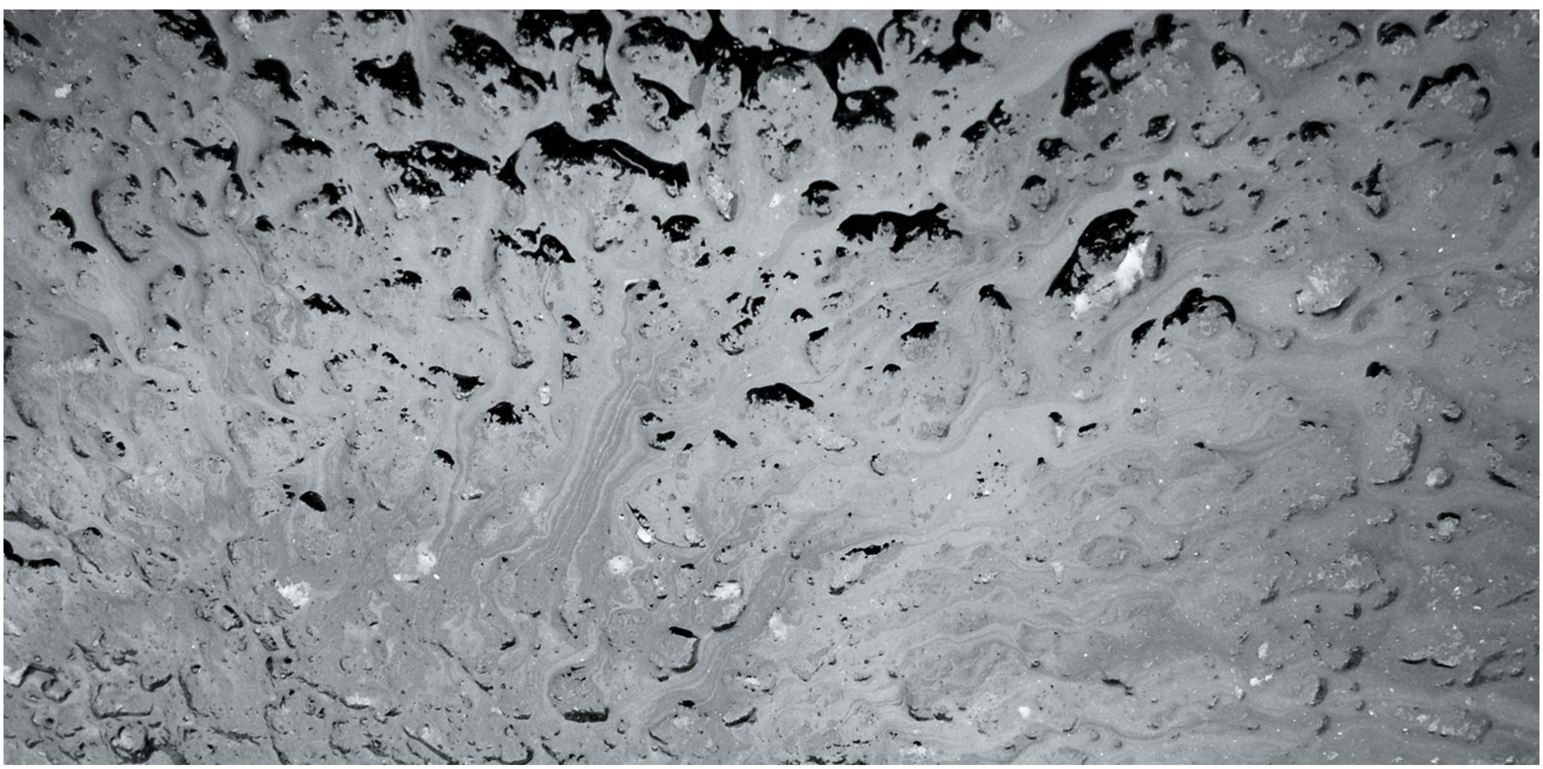


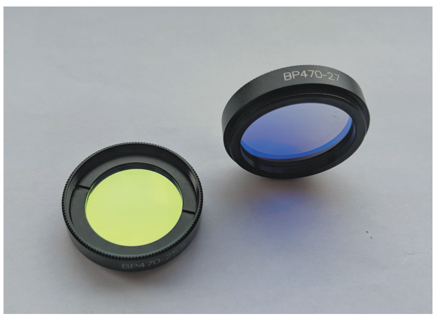
MAXIMIZING CAMERA PERFORMANCE WITH FILTERS

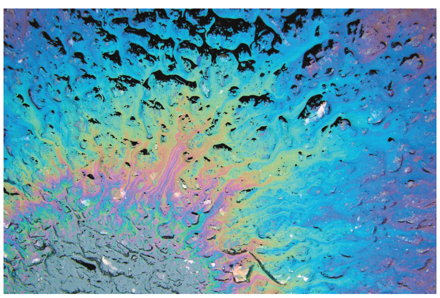
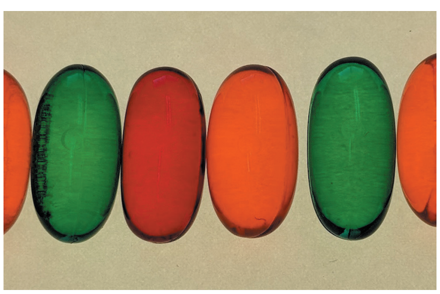
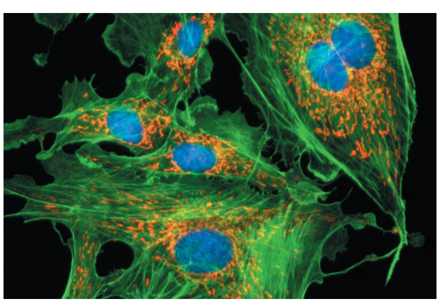
Understanding Filter Types
And Their Usefulness In Various Imaging Applications



TELEDYNE LUMENERA **WHITE PAPER**

MAXIMIZING CAMERA PERFORMANCE WITH FILTERS



WHAT'S INSIDE

INTRODUCTION

The use of filters allows a camera to be more selective with what kind of light will make contact with the sensor. Filters are often designed with the intent of blocking out a certain amount of light, whether this is a specific band of light (a set of color(s)) or by removing potential glare and improving contrast. Either way, the purpose of a filter is to reduce the light entering the camera. As such, the sensitivity of the sensor needs to be considered when choosing an appropriate filter.

Examples of filter types will be covered in following sections of this paper, along with a detailed explanation of filter theory. Additional examples will cover practical applications for filter use such as intelligent traffic systems (ITS), machine vision and inspection, precision agriculture, and multispectral imaging.

FILTER THEORY

There are two main ways to filter light based on wavelength: absorptive and dichroic filters. Absorptive filters, as the name suggests, are designed to absorb certain wavelengths and transmit others, giving the material a certain colour that corresponds to the wavelengths that it transmits. Various wavelengths are absorbed using a combination of chromophoric components within the glass. The term chromophoric refers to a group of chemicals called chromophores that are capable of absorbing a specific range of wavelengths.

Dichroic Filter Synonyms:

- **Reflective**
- **Thin Film**
- **Interference**

Dichroic filters are, by contrast, not necessarily visually indicative of the color they transmit. This is because they reflect instead of absorbing the undesired wavelengths.

For example, the filters in Figure 1 both transmit blue light (with a bandpass of 470 nm). However, the filter on the left looks green instead of blue because this filter is reflecting other wavelengths not in the bandpass region. The filter on the right is an absorptive filter which is only transmitting blue light.

DICHROIC FILTERS

Dichroic filters are made of thin layers of glass that have a range of high refractive indices. These filters work by spacing these layers evenly and, depending on the order, will result in a specific interference pattern. This results in an interference pattern that acts to reinforce the desired wavelengths and produce reflections of all other wavelengths. The pattern can be carefully tuned by controlling the selection, thickness, and number of optical coatings, thereby allowing for the creation of a wide range of filters.

Figure 1 - Two Identical Dichroic Bandpass Filters in the Blue Wavelength Region Illustrating Reflection vs Transmission

A similar effect can be seen with oil on top of water. When oil collects on water, as seen in Figure 2, the colors seen are coming from the different layers of oil reflecting specific wavelengths at each layer within the water.

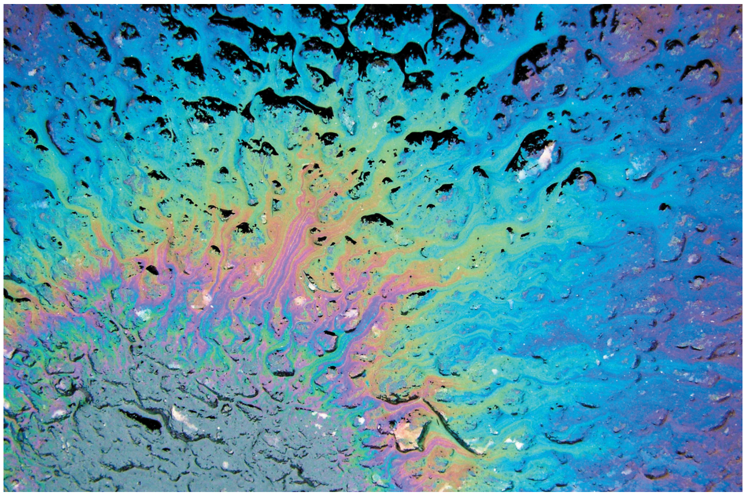


Figure 2 - Oil on Water Reflecting a Variety of Colors

AR COATING

Filters help block out unwanted wavelengths from reaching the sensor, but any filter will still have losses due to reflections. In an optical system it is important to maximize the desired wavelengths to achieve the strongest possible signal. Any filter or even glass elements will reflect at least a small percentage of light that translates to loss in the signal. When a number of glass surfaces are placed in sequence within the optical path, such as a multi-lens system, the losses are summed from each surface reflection. This reduction in transmission is the reason that each surface in the optical path should be treated with an antireflective (AR) coating.

Figure 3 - Illustration of the Effects of AR Coatings on Lens Filter Elements

AR coatings help reduce glare in various scenarios such as vehicle headlights during the night, which is critical for intelligent traffic systems (ITS). With a reduction in glare, there is an increase in the accuracy of optical character recognition (OCR) software that looks for license plates to read. A visual example of an automated license plate recognition (ALPR) system can be seen in Figure 3, where the image on the left is using a camera equipped with an AR coating versus the high amount of reflections seen in the right image.

FILTER EXAMPLES AND PRACTICAL APPLICATIONS

POLARIZER

Light is often referred to in terms of wavelengths, but how these waves are orientated is not as common of a consideration. The way light travels is determined by its polarization. Light from most common sources such as the sun or a lamp will emit non-polarized light, which means the oscillation of these waves is not in a single direction. However, there are several ways to alter the polarization. The most common type of polarized light is reflection off of non-metallic surfaces such as, bodies of water, glass windows, or asphalt.

Polarized light that has been reflected is usually unwanted in machine vision systems because it causes glare, making the details of the subject harder to discern. The removal of this unwanted light can be achieved using a polarizer filter.

A polarizer works by only transmitting light of a certain polarization. Light sources natively emit with mixed polarization and by applying a polarizer the transmitted light will have its intensity reduced because only a portion of that incident light will be properly polarized to be allowed through the polarizer. Light that is aligned in the orientation of the polarizer will be fully transmitted and reversely any light that is perpendicular to the filter will be completely blocked. Any light that is polarized in between 0° and 90° will have a portion transmitted in alignment parallel to the polarizer. When summed, these wavelengths total 50% of the available light, or one full stop. It is, therefore, important to note that when using a polarizer, compensations in f-stop, exposure time, or gain will need to be put into place to account for the reduction in transmitted light.

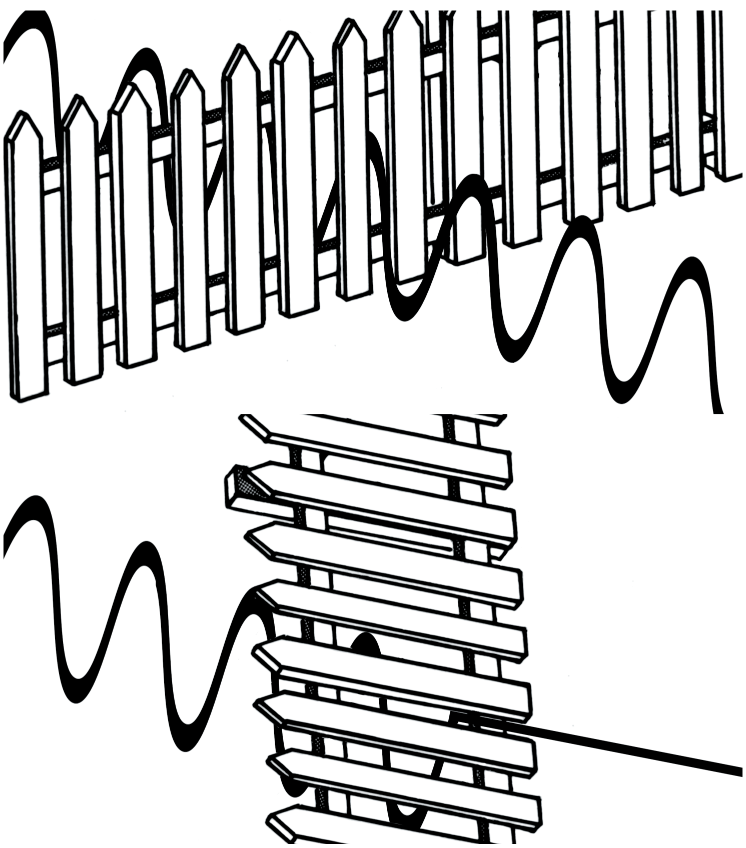


Figure 4 - Picket Fence and String Analogy to Describe Polarization

A simple analogy of this, illustrated in Figure 4, is of a string and a picket fence as the light wave and the filter, respectively. If a string is tied to a fixed point at one end of the fence and the other end of the string moves back and forth, a wave would form in the string. If that string were to pass through a picket fence, the wave would pass through the fence if the back and forth motion of the string corresponds to the orientation of the fence. Conversely, if the back and forth motion is perpendicular to the orientation of the fence, the wave in the string would not pass through the fence

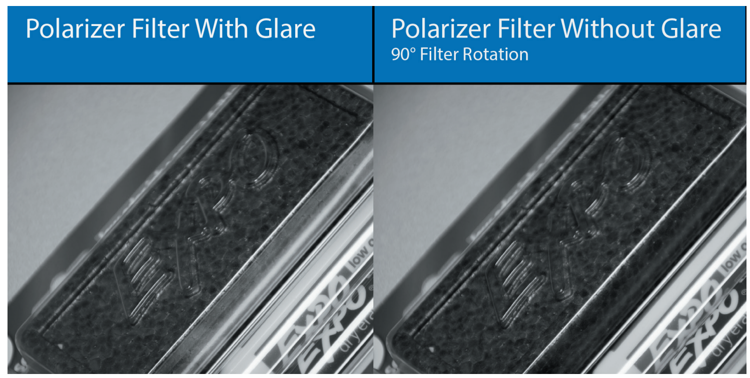


Figure 5 - Impact of a Polarizer Filter on Glare Reduction for Inspection

There are a number of practical applications for polarizer filters when it comes to machine vision. Since these filters help to dramatically reduce glare, they can be used in packaging inspection for plastics, labels, and other non-metallic surfaces. The example in Figure 5 shows the effects of a polarizer filter used in a vision system to inspect whiteboard markers and cleaning supplies in their packaging. The images illustrate the effect of rotating the filter 90° to show and then hide the glare in the plastic packaging. When used properly, the polarizer filter can remove a significant quantity of glare, increasing the signal to noise ratio.

DUAL BANDPASS FILTERS

Dual bandpass filters allow for two distinct regions of specific wavelengths to transmit. Typically, bandpass filters are used with color cameras that are treated as multispectral imaging devices.

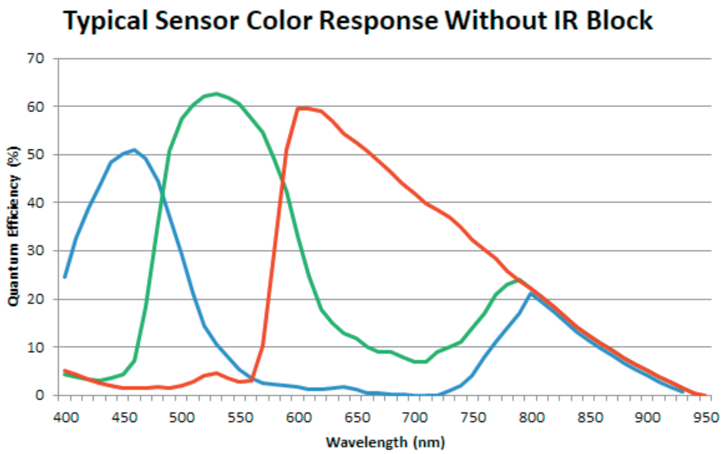


Figure 6 - Typical Color Sensor Response Without IR Blocking Filter

FILTER “MATH”

To use a dual bandpass filter on a color camera it helps to understand the effects of the camera’s color filter array (CFA). The graphic in Figure 6 illustrates the typical response of a color camera without the color-balancing effect of infrared (IR) blocking filter. Adding a dual bandpass filter with the IR filter allows the camera to target specific spectral bands through the three (red, green, blue) color channels. The graph in Figure 7 illustrates the response of a visible + near-infrared (NIR) dual bandpass filter, where Figure 10 shows a much narrower response from a 475 nm + 850 nm (blue + NIR) filter. The following sections will elaborate on these two filters and give examples that highlight their benefits.

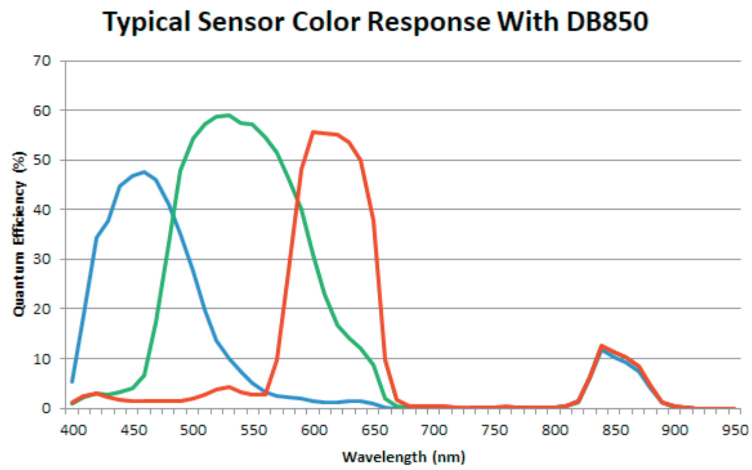


Figure 7 - Color Sensor Response When Using Visible + 850nm Dual Bandpass Filter

VISIBLE + NIR FILTER FOR INTELLIGENT TRAFFIC SYSTEMS

Using a regular color camera with an infrared flash simply will not work due to the IR blocking filter. However, replacing this filter with a dual bandpass visible + NIR filter allows the camera block most infrared light. This will take advantage of the camera’s sensitivity to these wavelengths that are invisible to the human eye.

As an example for this paper, a demonstration system was created using a Lumenera Lt345RC color camera with a MidOpt DB850 dual bandpass filter, a Kowa LM16JC5MM-IR IR-corrected lens, and a Metaphase LRS725 infrared light.

The IR-corrected lens is used to ensure that its focal point is maintained across all wavelengths. If a non-IR-corrected lens were used, it would have two distinct focal points: one where images are in focus when under white light, and another when under infrared light. IR-corrected lenses typically require extra elements to ensure the focal points of all wavelengths converge at the same point behind the exit pupil. For this reason, the lenses typically have higher costs than uncorrected variants. They are, however, absolutely necessary to achieve sharp images across all wavelengths without refocusing the lens.

The system created for this demonstration blocks a significant portion of NIR light to maintain enough color accuracy to correctly identify the color of a vehicle during the day, while at night allowing enough NIR light to clearly make out the vehicle's licence plate. A daytime comparison between the demonstration system and a typical color camera can be seen in Figure 8.

Figure 8 - Daytime Comparison between DB850 filter and IR Block Filter

While color accuracy is not perfectly maintained due to the small amount of NIR light making its way to the sensor during the day, it is still sufficient enough to correctly identify the color of the car that it is imaging. In the enlarged color chart, the color differences are barely noticeable to the human eye. However, the color discrepancies are much more noticeable in the trees behind the cars since they reflect a high amount of NIR light to protect themselves from overheating. Since this application is targeting vehicles, there is no concern about the color shift present in vegetation.

To further increase the color accuracy of the system, a color correction matrix can be applied to the camera during daylight hours to help offset the NIR light generated by the sun.

As for imaging at night, Figure 9 illustrates how the IR strobe brings out the detail in the vehicle's licence plate, making it easily readable by optical character recognition software. The image itself looks monochrome because each color channel's response is roughly the same at 850 nm and produces a gray-scale-like image.

Figure 9 - Night Image Using a Color Camera, Dual Bandpass Filter, and NIR Strobe

BLUE + NIR FILTER FOR PRECISION AGRICULTURE

Imaging vegetation for precision agriculture is typically done using specific spectral bands and then preforming analysis on the resulting images. A common way of capturing the images is through the use of one monochrome camera per spectral band with a bandpass filter on each camera to isolate the required wavelengths. While this is the preferred method as both spatial and spectral resolutions are maximized, there are cleverways of obtaining comparable results through the use of dual bandpass filters.

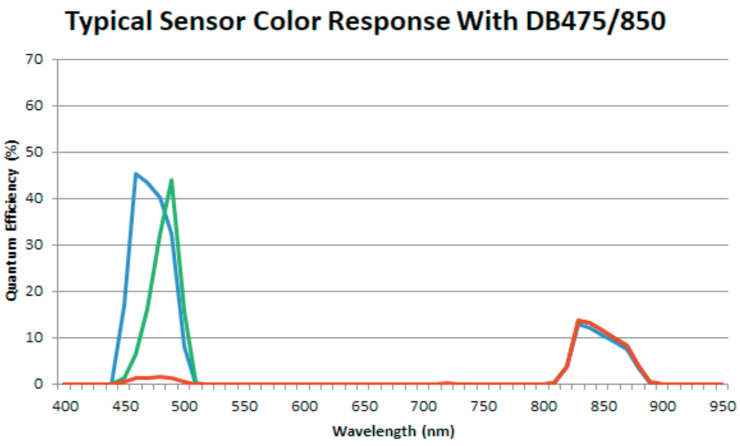


Figure 10 - Color Sensor Response with 475nm + 850m Dual Bandpass Filter

One such example, as elaborated in our Solution Sheet: How to Perform Vegetation Analysis With a Single Camera, is through the use of a color camera and a dual bandpass filter targeting the blue and near infrared spectral bands. This particular example offers an alternative to a two-camera system for the calculation of the normalized difference vegetation index (NDVI), particularly for use with unmanned aerial systems where size and weight requirements are a concern.

NDVI evaluates the difference between the reflected red and NIR wavelengths from vegetation to determine the health of the plants. Plants that appear healthy and green are reflecting lots of infrared light to prevent the plant from overheating as well as a larger quantity of green light when compared with red and blue light, which is absorbed during photosynthesis. Tweaking NDVI to measure blue light instead of red allows the camera to use the blue channel to monitor the absorbed light for photosynthesis and the red channel for the reflected NIR light.

The red and blue channels are then used to calculate a modified ratio to approximate the results of the NDVI calculation. The results will range from -1 to +1 where negative numbers tend to correspond with inorganic materials. Healthy vegetation typically falls between 0.2 and 0.8. For easier visualization, color maps are applied to the NDVI image. The example in Figure 11 uses blues to illustrate negative NDVI values and progresses from green to red for positive values.

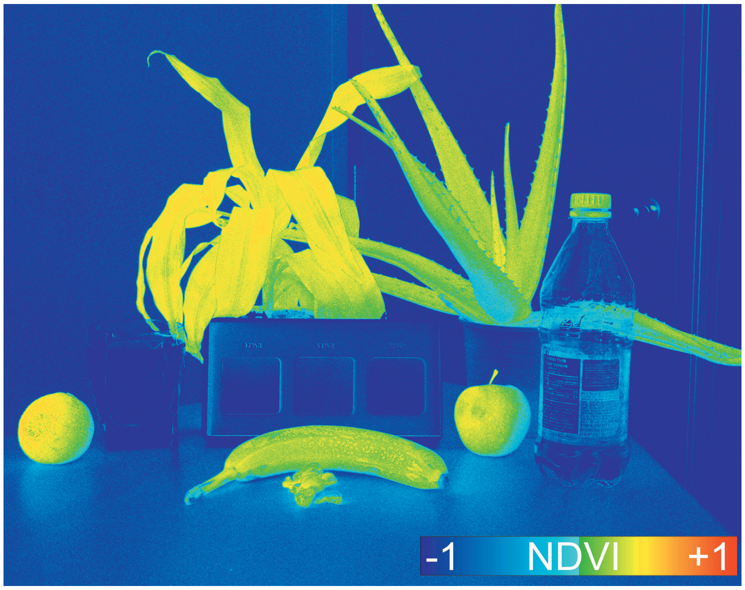


Figure 11 - Approximate NDVI Image Captured with a Single Color Camera and Blue+NIR Dual Bandpass Filter

CONTRAST ENHANCEMENT

Machine vision thrives in areas of high contrast, allowing for better tolerances and fewer errors. Since machine vision is typically performed in grayscale, filters can help increase contrast between two objects of similar color or dramatically highlight objects of different colors. To illustrate this, the following example shows a series of backlit colored gel capsules, pictured in Figure 12, imaged with various bandpass filters to increase the contrast between the capsules.

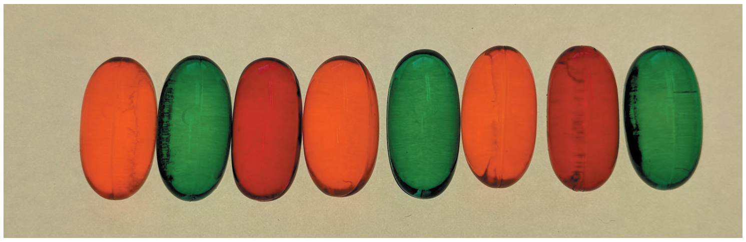


Figure 12 - Backlit Gel Capsules in Color

As shown in Figure 13, the grayscale intensity differences between colored gel capsules are quite similar despite the differences in the color of the capsules. A yellow line is used to illustrate from where the pixel intensity graph generates each value. The dips in greyscale intensity correspond to each capsule. The peaks are representative of the gaps between each capsule. The intensity values for each capsule are quite similar, regardless of color, and fall within 50 digital number (DN) of one another. This indicates a poor contrast ratio and makes it very difficult for a machine vision system to discern one color from another.

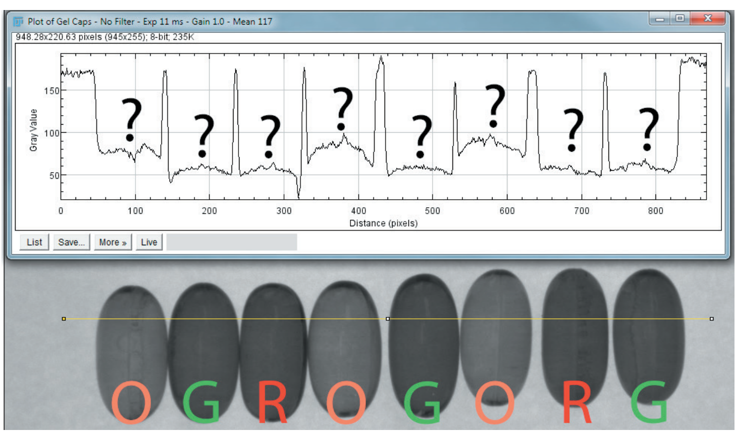


Figure 13 - Machine Vision System Unable to Discern the Differences in Color

Adding a red bandpass filter to the imaging system creates a substantial increase in contrast between the green and other capsules, as seen in Figure 14. The green capsules have an intensity value near zero while the red and orange capsules are well above 150 DN. This heightened contrast ratio significantly improves the accuracy of a machine vision system tasked with sorting the green capsules from the orange and red.

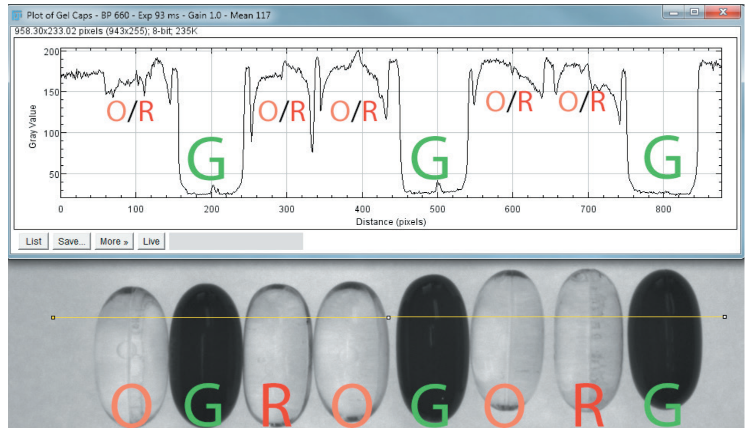


Figure 14 - Machine Vision System with a Red Bandpass Filter to Increase SNR Between Green and Orange/ Red

However, if the system were tasked with distinguishing the orange capsules from the green and the red, a different filter would be required. Using an orange bandpass filter centered on 590 nm creates a larger contrast ratio between all the capsules, as can be seen in Figure 15. The intensity values for each colored capsule fall in three distinct ranges: below 50 for the green capsules, between 50 and 100 for the red capsules, and between 100 and 150 for the orange capsules. This is because the orange capsules transmit a large amount of light in the 590 nm range, whereas the red capsules transmit some, and the green capsules transmit very little.

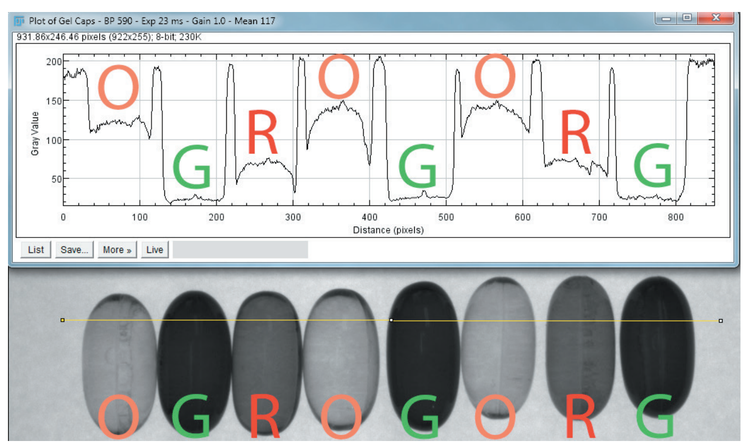


Figure 15 - Machine Vision System with an Orange Bandpass Filter to Increase SNR Between All Three Colored Capsules

MULTISPECTRAL IMAGING USING A FILTER WHEEL

A series of filters can be inserted in a spinning filter wheel placed directly in front of a camera lens. With a mono camera, as a filter wheel rotates it will expose the sensor to a sequence of narrow range of wavelengths. For every image taken, the wheel will move one filter forward in the sequence.

Figure 16 - Example of a Filter Wheel

As long as the subject is stationary, using a filter wheel is a great method for capturing multispectral imaging. Spectral bands are limited only by the number of filters available, and as previously explained, dichroic filters can be custom made to have very specific bandpass widths and wavelengths.

The following example in Figure 17 shows two rose plants with yellow flowers at six specific wavelengths. The plants and flowers absorb nearly all blue light and reflect a large amount of infrared light to prevent them from overheating. The flowers also seem to equally reflect a large amount of green, orange, light red, and dark red light, which explains their yellow color. The plant also absorbs a significant amount of light in the reds while absorbing less as the wavelengths approach 525 nm, giving the leaves a green color. The higher green reflectance is expected from a healthy plant signifying that photosynthesis is taking place.

Further mathematical computations on these images can lead to in-depth vegetative analysis. For instance, the bottom two images can be used to compute the Normalized Difference Vegetation Index (NDVI) to determine the plant's overall health.

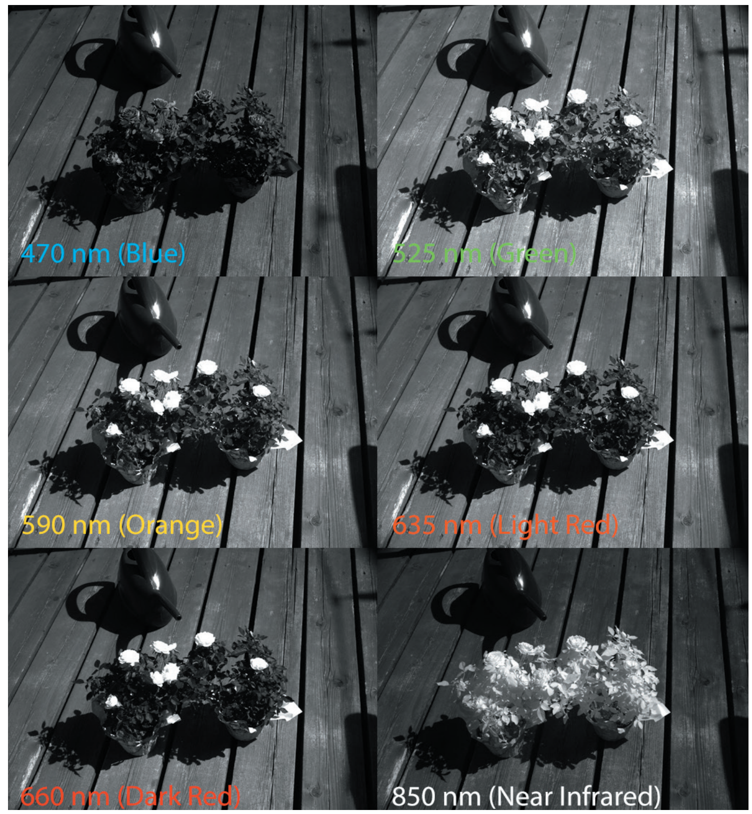


Figure 17 - Two Yellow Rose Plants Imaged at Six Separate Wavelengths

Filter wheels are also used in a similar fashion for fluorescence microscopy. Using dichroic filter cubes, the wheel can pass a specific excitation wavelength to the sample. The camera can then capture the shifted fluorescing wavelength from the sample. Stains are used to qualify or quantify compounds in the sample and anywhere from two to six images are captured at different excitation wavelengths to create a composite image such as the one found in Figure 18.

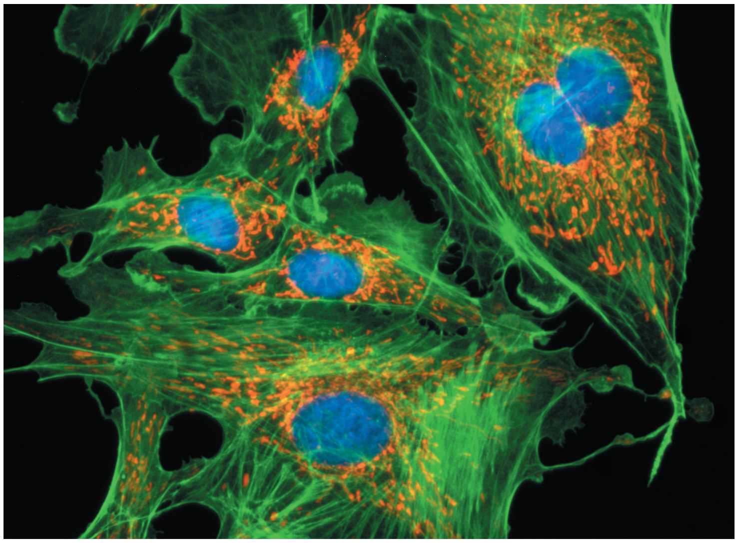


Figure 18 - Fluorescence Microscopy Captured Using Three Separate Dichroic Filter Cubes

CONCLUSION

By narrowing the type of light that can reach the camera sensor, images can be drastically improved. When working with machine vision systems it is important to consider what specific subject matter is being captured so that a proper filter strategy can be designed. Unwanted reflections can be targeted with AR coatings and polarizers, whereas better identification of subjects can be achieved with bandpass filters that best isolate the specific wavelengths of interest. The examples in this paper aid as an introduction to using filters but different applications can also make use of the same benefits.