Sensors

January 16, 2015

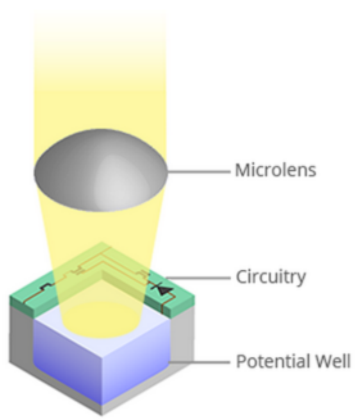
1 Pixels

A digital image sensor is a grid of small light-sensing elements called picture elements, or pixels.

The pixel's detector (shown in blue) is generally made of silicon and is "sensitive" to light. When light strikes the pixel, some of its energy is transferred to the electrons inside the silicon atoms. If the energy is high enough, the electrons dislodge from their parent atoms. This is called the photoelectric effect.

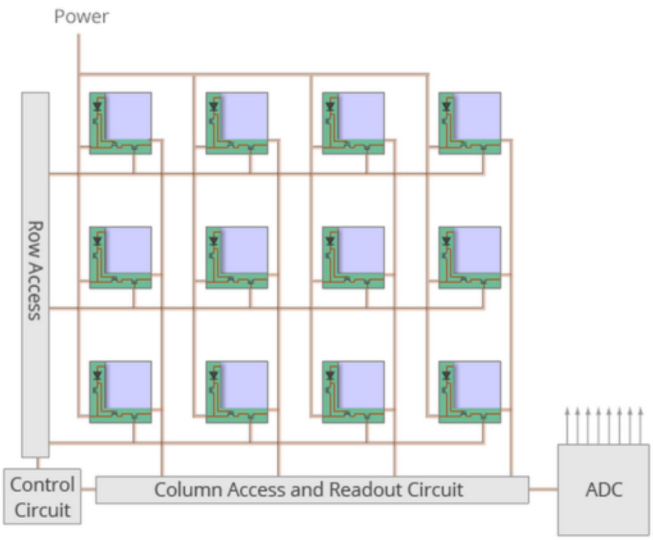
The freed electrons are collected in a bucket-like region known as the potential well. The number of freed electrons – the amount of charge that builds up in the potential well – directly depends on how much light falls on the pixel. The stronger the light, the more electrons are freed. Therefore, the voltage in the potential well is a measure of the image brightness at that pixel.

In CMOS sensors, each pixel has its own circuitry for measuring the voltage of its potential well, and is equipped with a microlens (a tiny lens) that focuses the incoming light away from the circuitry and onto the detector. Thus, each pixel is able to capture all the light focused by the imaging lens onto it.



2 Grid of Pixels

An image sensor is usually a two-dimensional grid of pixels. The number of pixels on the grid is called the resolution of the image sensor. The voltages of the entire grid of pixels are read out one pixel at a time and converted to numbers by the analog-to-digital converter (ADC).



The end result of the read-out process is a two-dimensional array of numbers that is called a digital image. Each number represents the light energy falling at the corresponding pixel. In an 8-bit sensor, black is 0, white is 255, and all the numbers in between are shades of gray.

100	100	0	0	0	0	255	255
50	0	50	50	50	50	255	255
50	0	50	255	255	255	255	255
50	0	50	255	255	255	255	255
50	0	50	255	255	255	255	255
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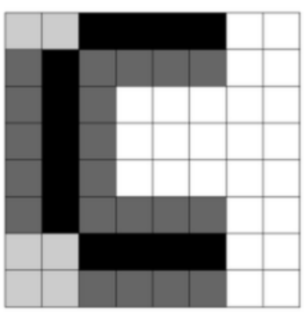
100	100	0	0	0	0	255	255
100	100	50	50	50	50	255	255

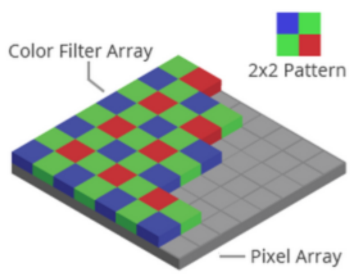


3 Colors

Most image sensors, employs a mosaic of tiny red, green and blue color filters, each filter positioned just beneath the microlens of a pixel. A popular design for the mosaic is the Bayer pattern. Now the question is, how do we estimate the red, blue and green light falling on any given pixel, if it is able to receive only one of the three colors – red, blue or green?

Let us assume the number at each pixel to be the amount of red, green, or blue light it detects. For example, the red component of the center pixel is 246, but its green and blue components are unknown. The two missing colors are estimated using the green and blue measurements made by neighboring pixels. This process is called interpolation.

The simplest way to interpolate the missing values is to average the values of neighboring pixels of the same color. This way, each pixel will have three values – the actual value of the color it measures through its filter, as well as two interpolated values for the two missing colors. The interpolation is applied to each and every pixel to obtain a full color image. The color interpolation process is known as demosaicing.



4 CMOS vs CCD

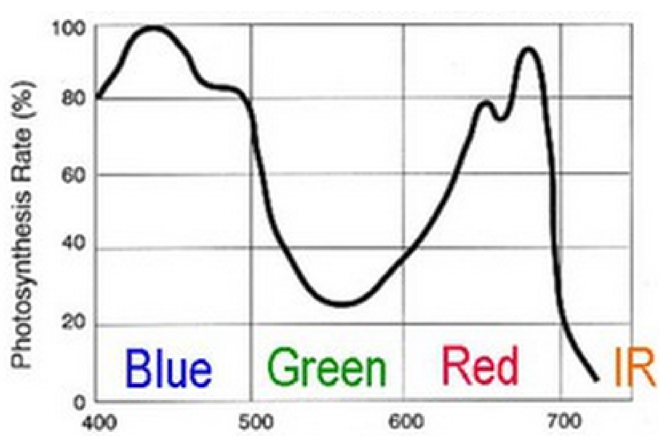
Both CCD (charge-coupled device) and CMOS (complementary metal-oxide semiconductor) image sensors start at the same point: they have to convert light into electrons. The next step is to read the value (accumulated charge) of each cell in the image. In a CCD device, the charge is actually transported across the chip and read at one corner of the array. An analog-to-digital converter turns each pixel's value into a digital value. In most CMOS devices, there are several transistors at each pixel that amplify and move the charge using more traditional wires. The CMOS approach is more flexible because each pixel can be read individually.

- CCD sensors create high-quality, low-noise images. CMOS sensors, traditionally, are more susceptible to noise. Because each pixel on a CMOS sensor has several transistors located next to it, the light sensitivity of a CMOS chip tends to be lower. Many of the photons hitting the chip hit the transistors instead of the photodiode.

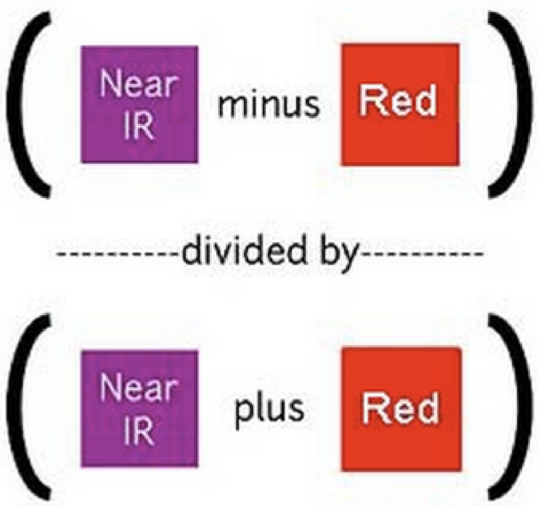
- CMOS traditionally consumes little power. Implementing a sensor in CMOS yields a low-power sensor. CCDs use a process that consumes lots of power. CCDs consume as much as 100 times more power than an equivalent CMOS sensor.
- CMOS chips can be fabricated on just about any standard silicon production line, so they tend to be extremely inexpensive compared to CCD sensors. CCD sensors have been mass produced for a longer period of time, so they are more mature. They tend to have higher quality and more pixels.

5 NDVI

Vegetation is green because plant leaves reflect green light. Instead they use lots of the blue and red wavelengths in sunlight. The pigments in leaves absorb this light to power photosynthesis which converts CO2, water, and nutrients into carbohydrates (food). In general, you can estimate the productivity or vigor of vegetation by how much blue and red light it is absorbing. Photosynthetic pigments do not use the longer, invisible wavelengths of near infrared light and reflect almost all of it away (this helps prevent the leaves from overheating).



Shortly after the launch of the first Landsat satellite in 1972, scientists began using the data from its sensors to estimate the productivity of vegetation by comparing the amount of red light reflected (there is not much from healthy plants) to the amount of near infrared light reflected (there is a lot). The amount of infrared light reflected from vegetation is a good indicator of how bright the sunlight was at any moment (leaves reflect almost all IR). Comparing that to the amount of reflected red light can suggest what proportion of the sunlight was being absorbed by the plants.



That relationship is a good measure of the amount of photosynthetically active biomass. They quickly settled on an index of plant productivity called NDVI for Normalized Difference Vegetation Index. Instead of just using the difference between the amounts of red and near infrared light, they normalized that difference by dividing it by the total amount of red plus infrared light. That allowed the index from different areas and different times of the day or year to be compared with each other.

6 NDVI from Digital Cameras

Unlike the human eye, the silicon-based sensors in digital cameras are sensitive to both visible and near infrared light. To prevent infrared light from being recorded in standard digital cameras, a filter opaque to IR is placed in front of the sensor. The resulting color sensitivity of digital cameras mimics human vision.

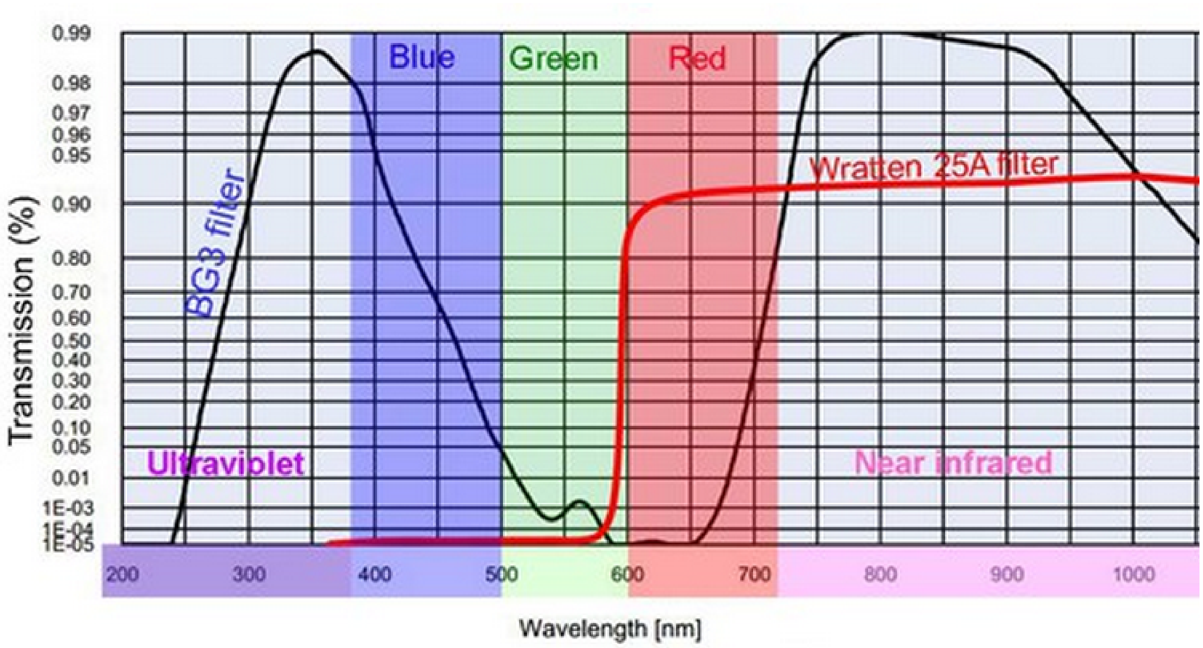
Solution A

It is possible to produce a good approximation of NDVI by using a normal consumer grade digital camera to capture visible light (by applying photo manipulation software to isolate the red channel in a digital image file), and another similar camera modified to capture only near infrared light (by filtering the visible wavelenghts with the usage of a color negative film in front of the sensor).

Notice that in the modified IR cameras, any one or any combination of the color channels from these cameras could be used for near IR information, although more IR light might be available in one of the channels.

Solution B

It is also possible to capture all the information needed to compute NDVI in just one camera.



SUPERBLUE FILTER

The standard IR block filter is replaced by a Blue Filter that passes IR and blocks only red light, so the red channel will record mostly IR light. The blue channel which will record normally can be used to represent wavelengths that are absorbed by plants.

The available superblue filters do not block all red light, so the channel used for infrared light will be contaminated with visible red wavelengths. The blue channel which is used to represent wavelengths absorbed by photosynthetic pigments will also record some green light and probably some infrared light. Much testing is required to learn the biological meaning of these versions of NDVI.

RED FILTER

The standard IR block filter is replaced by a Blue Filter that passes IR and blocks all visible light except for red, so the blue channel captures a very pure NIR signal. To compute NDVI, the blue channel is used for NIR and the red channel is used for red visible light.

Interpreting vegetation health is often more straightforward when the red channel is used to represent the light that plants use for photosynthesis, and red light is not scattered by the atmosphere as much as blue.