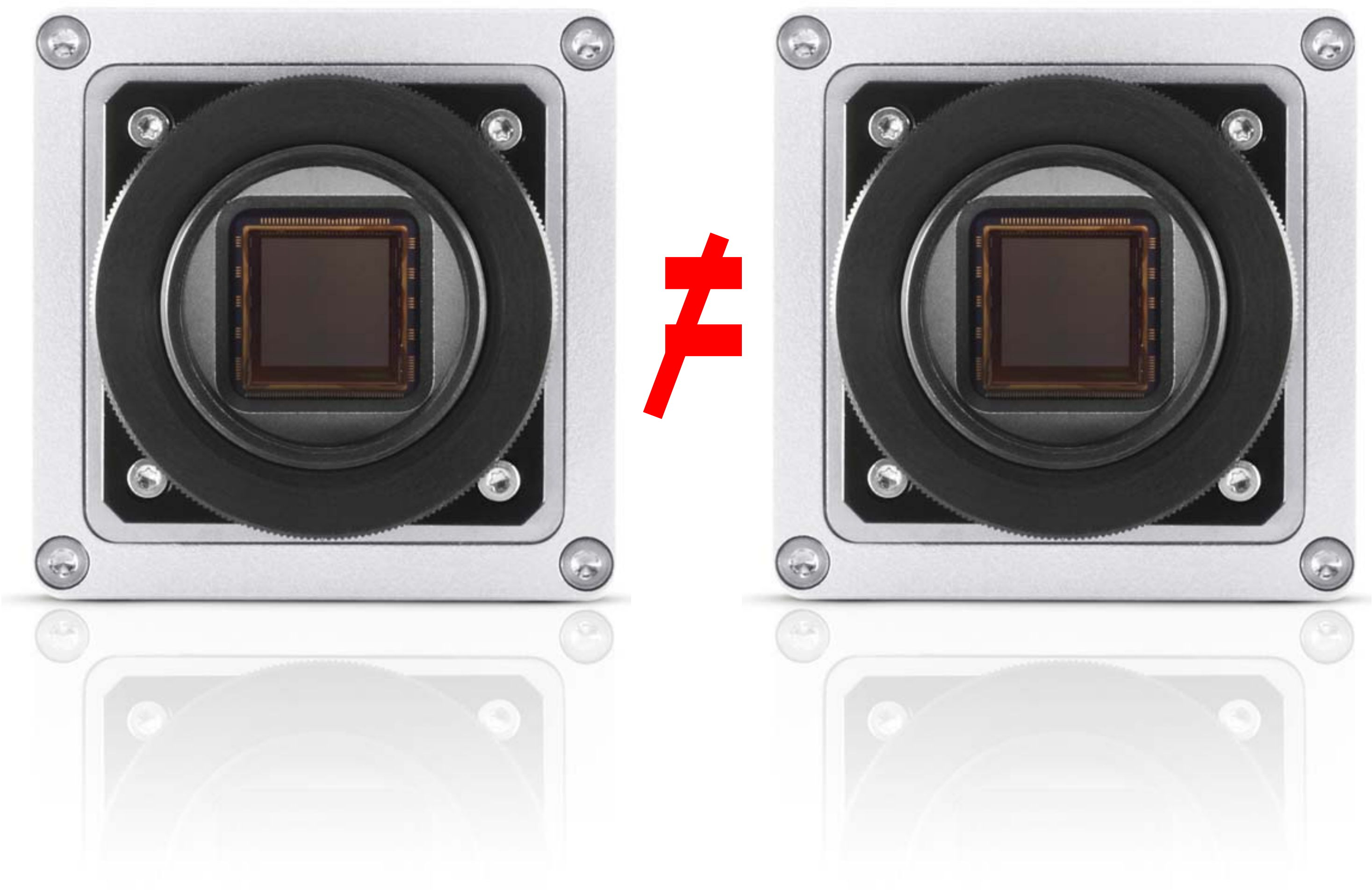
E-paper

Machine Vision Image Sensors vs. Cameras

What camera technology adds to make a better picture



Adimec
Excellence in Imaging

Contents

1. Introduction

It is not surprising that many industrial OEM system builders begin their machine vision system specification based on the image sensor they will use. The sensor has a great influence on critical performance requirements for a specific application.
Once an image sensor is selected, OEM system developers typically consider cameras that contain that particular image sensor, and then base their final decision on baseline needs such as camera outline and unit price. While image sensor selection and basic camera characteristics are both important, it is also important to understand that not all cameras are created equal, even if they use the same image sensor.

To find a complete and optimized solution to an application's needs, OEMs should carefully look at value-added capabilities and features that camera developers offer to enhance and augment the image sensor. These additional capabilities can greatly improve accuracy, performance, and scalability. In addition, they should determine whether the camera builder has not distorted the image sensor signal but improved it. Ultimately the long-term ROI of the entire system is greatly influenced by the camera and camera supplier; examples are camera performance, requirements for upgrades and replacement, reliability, future roadmap alignment, and support. This paper will review a range of features and capabilities high-performance camera developers are offering in addition to the commercially available image sensors on the market.

2. Start with the image sensor, but then keep going

Starting a machine vision system definition with the image sensor is a natural thing to do. The image sensor is an extremely critical component of a camera and determines many critical parameters of the camera including:

- Resolution and pixel pitch
- Frame speed (fps)
- Monochrome or color
- Sensitivity (QE)
- Dynamic Range
- Read Noise
  (e.g. stability over time, temperature, or specific artifacts)

However, the fact that several cameras use the same image sensor does not mean the cameras from different vendors will produce the same image, or even meet the requirements of specific vision applications. Camera manufactures have different strategies and focus which leads them to create different types of products. Industrial cameras can generally be divided into three categories:

1. General Purpose Cameras – designed to be small and low cost for broad appeal to many markets and applications. Customers are typically system integrators.

2. High-Performance Cameras – designed with the needs of a specific application in mind with optimized additional functionality and tightly controlled manufacturing. Some customization is offered to further improve fit into the OEM system. Customers are typically OEMs where the camera is a critical component of the system.

3. Scientific Grade Cameras – optimized for just 1 or 2 aspects such as highest resolution or highest sensitivity for very specific scientific use. Size, weight, and cost are not as important. Customers are typically **scientific laboratories and research institutions.**

It is important to consider if a general purpose camera is acceptable for your system or if a high-performance camera would be more appropriate, actually reduce overall system costs and increase the value of the OEM equipment offered to the end customer. High-performance camera manufacturers add to the image sensor in ways that are optimized and valuable for OEMs, such as:

- Algorithmic functionality and advanced Image Processing
- Design and Manufacturing for Repeatability and Reproducibility
- Interface Options

How the camera developer addresses each of these requirements can help in making a final decision for a camera on which to build a system..

3. Functionality/Processing

The camera manufacturer can add a wide variety of functionality beyond the core capabilities of the image sensor - improving and adding to what the image sensor can do. These features can include:

1. Spatial noise reduction (uniformity correction)
    - Flat field correction
    - Channel matching
    - Shading correction
2. Temporal noise reduction
    - Frame averaging (SNR increase by $\sqrt{N}$ where N is the number of accumulated electrons in the pixel)
    - Binning (on-chip or off-chip)
3. Dynamic range expansion
    - Frame averaging
    - Binning
    - Combining images with various integration times
4. Data representation change
    - Video enhancement
    - Edge enhancement
    - Look-Up Table or LUT (e.g gamma)
    - Image Rotation
    - Color processing
    - Region of Interest (readout)
    - Electro-Optical system calibration

There are several advantages of having advanced functionality/processing on-cameras as opposed to doing this off the camera and elsewhere in the system, such as:

- Higher accuracy since a higher bit depth is available for image processing before the images are sent over the interface link.
- Greater effectiveness as calibrations are made closer to the source of the artifacts and experienced camera manufacturers have a thorough

understanding of potential issues. A good camera provider has years of experience on how to drive the image sensor chip and get an optimized image out.

- Reduced costs through::
    - Fewer software resources to create own image processing or workarounds for inefficient camera performance.
    - Reduced load on the PC-framegrabber processing can mean less expensive overall system costs.
    - Reduced data rate can allow for cost optimization with the system connectivity infrastructure. For example if images are processed in the camera a 2-tap CameraLink interface could be sufficient to transport the results rather than a 10-tap configuration
- Faster throughput with data reduction prior to the interface (Region Of Interest (ROI), compression, bit reduction)
- Automatic adjustments through direct loops that either adjust for temperature changes, lighting conditions, lens defects or other specific system conditions.

Below is a more detailed look at some examples of these types of enhancements and their benefits. We are constantly updating our blog with more information on camera functionality capabilities and other related topics. Please check for the latest information:

http://info.adimec.com/blogposts/

3.1 Spatial Noise Reduction (Uniformity Correction)

There are no perfect components, and that includes image sensors and lenses. Even with very high quality CCD and CMOS sensors, sensors produce artifacts. With CMOS sensors, inter-frame stability can be a concern. There are also non-uniformities between pixels. Each column can have a different dark current and a different sensitivity which is further complicated by non-uniformities from pixel to pixel. For CCD image sensors, there are non-uniformities from each output (channel). Even more dramatically, channels, columns, and pixels may show different non-linearity characteristics.

For measurement techniques that rely on the details in the image, poor uniformity impacts the accuracy. In order to correct for these, the camera manufacturer needs to completely understand the mechanisms in the sensor causing the artifacts. With this understanding, modeling can be done and appropriate calibrations can be created. This allows for the artifacts to be compensated for during production and, more importantly, in real time to adjust for the specific conditions of the system.

3.2 Flat Field Correction (FFC)

Flat-Field Correction (FFC) can be done with both CCD and CMOS-based cameras to correct for sensor artifacts, lens artifacts, and illumination artifacts (shading). The purpose of flat field correction is to ensure image uniformity regardless of exposure.

With CMOS sensor-based cameras, FFC is especially important to minimize or even remove sensor artifacts and improve the image uniformity. "Image-maps" are created and stored in the camera to calibrate the image sensor for equal response of all of the pixels. For some cameras, there is an automatic loop to control adjust the calibration for temperature changes.

The result of an example calibration can be seen in the images below, which show how they can improve the camera performance drastically. This saves on complex calibrations and adjustments in the system's frame grabber or CPU/GPU.

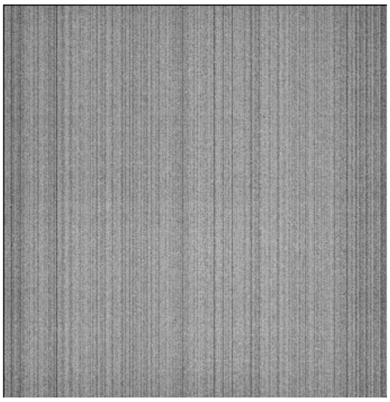


Figure 1a.
Image from a CMOS sensor without FFC (enhanced contrast)

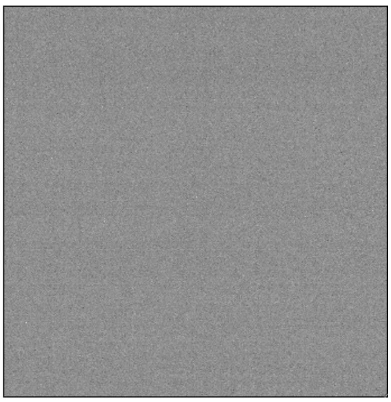


Figure 1b.
Image from a CMOS sensor after FFC applied (enhanced contrast)

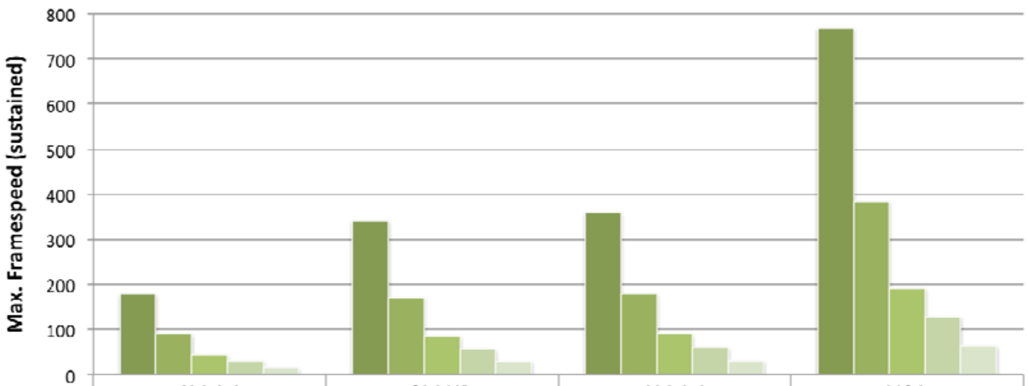
The drastic uniformity improvement by FFC can be seen in the images below. On-camera implementation of FFC saves on complex calibrations and adjustments in the system's frame grabber or CPU/GPU and provides a ready to use image for the application's dedicated algorithms.

3.3 Temporal Noise Reduction and Dynamic Range Expansion

Temporal noise varies with time and includes shot noise and read noise. Temporal noise reduction techniques can be used to reduce shot noise and read noise, and as a result increase the dynamic range of the camera. Shot noise is caused by randomly arriving photons on the surface of the sensor. As a result, shot noise is one noise source to take into account, especially in applications where the measurement relies on detecting details in the lighter parts of the image:

Binning and averaging to reduce noise

Noise can be reduced to increase dynamic range by two techniques or a combination thereof: **binning** and **averaging**. Binning reduces electronic circuitry noise and frame averaging reduces both electronic circuitry noise and shot noise. In some of Adimec's cameras, both functions can achieve noise improvements of up to +12 dB in the performance of the sensor. With binning, the resolution of the camera will be decreased but the maximum camera frame speed remains intact. Using frame averaging, the resolution of the camera will remain the same but the maximum frame speed of the camera drops. A compromise between shot noise improvement through averaging and speed can be found by applying ROI imaging (e.g. ROI imaging increases the acquisition speed of the camera which can be used to compensate for the drop in speed by averaging).



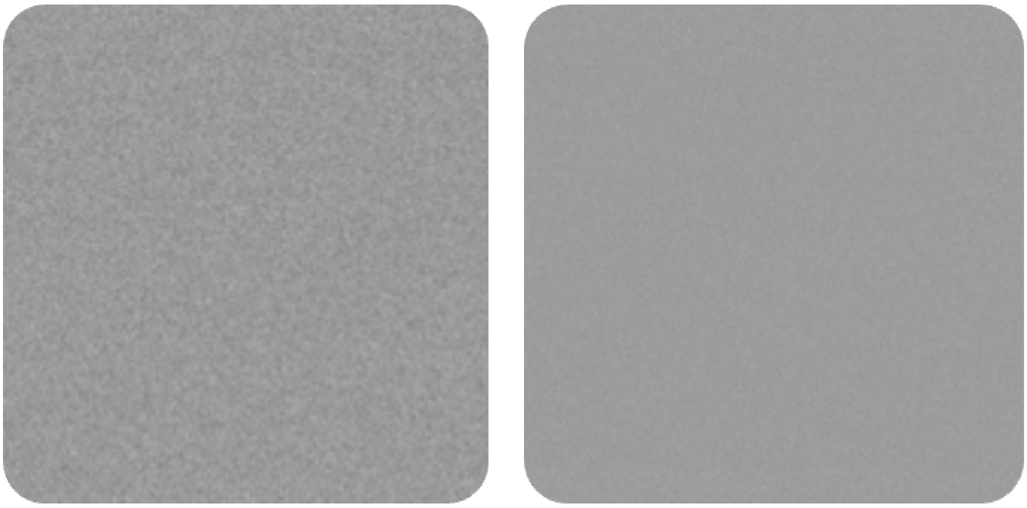
	4M 1:1	2M HD	1M 1:1	VGA
60 dB	180	341	360	768
63 dB	90	171	180	384
66 dB	45	85	90	192
68 dB	30	57	60	128
72 dB	15	28	30	64

Figure 2. Frame Speed of the Adimec Q-4A180 for various noise improvement scenarios

In the past shot noise critical measurements could only be addressed in cameras with the use of sensors with high full well, e.g. 40kel and higher. Although shot noise dominance can be controlled this way, acquisition speeds are often too low for today's needs. Sensors that are able to address the speed needs, in general, have low full well levels in order to achieve their performance. As these sensors also have lower read noise levels, similar and even better dynamic ranges are achieved. But this dynamic range number can be misleading: shot noise at lower full well levels becomes a more dominant noise source for impacting accurate detections in 'white'.

Shot noise reduction with frame averaging is the perfect example of optimizing system costs through processing in the camera as it reduces the data load on the camera interface and PC-framegrabber processing.

Secondly, averaging within the camera is performed with a bit depth and frame speed not possible in Camera Link-based framegrabber environments. High data rates with Camera Link are restricted to 8 bits per pixel. Averaging in the PC/framegrabber at high acquisition speeds (> 80 fps with 4Mpx) is therefore based on 8 bits input only, whereas the Adimec QUARTZ camera uses the full 10 bits from the sensor. This makes for higher accuracy in averaging results.



No Average **Average (+10dB)**

Figure 3. Example of dynamic range expansion with binning and averaging (enhanced contrast)

3.4 Data Representation Change

Once the raw image is captured, adjustments may significantly improve the final image. For instance, video contrast enhancement can allow for visibility in images despite extreme conditions. Or, accurate color processing involving complex techniques beyond what is commonly known, can allow for more advanced inspection and measurement.

Video enhancement

Camera developers often offer video enhancement options to deliver increased functionality. Adimec's Video Contrast Enhancement Module (VEM), for example, automatically improves performance and accuracy in low contrast conditions. The VEM technology eliminates the effects of a hazy atmosphere due to fog and/or sunlight scattering. Using this technology gives the system the capability to "see through fog." Even in diffused scenes where no details are visible, a remarkably detailed picture is presented. In near-dark applications, the automatic gain control gives an acceptable picture far beyond normal CCD sensitivity.

The VEM automatically adjusts important aspects of contrast enhancement, such as gain control, black level control, exposure control and contour correction. It offers the user as much control as required, including allowing the user to define the active measurement window.

VEM works in conjunction with Automatic Gain Control (AGC) and Automatic Exposure Control (AEC) features to make the contrast of the image as high as possible.

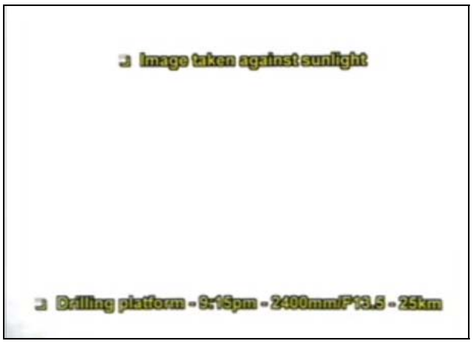


Figure 4a: The scene without VEM

Figure 4b: The same scene automatic light control applied

Figure 4c. The same scene with light control and contrast enhancement (VEM)

Color processing

Color processing is critical to many applications, both in terms of speed and accuracy. In general, it is best if color processing is in the camera (rather than off it), utilizing more bits for the processing.

Let's use a Bayer pattern sensor as an example. In such a device, each pixel collects data for one of the three Bayer primary colors (RB, GB, or BB). Alternatively put, the image consists of three sub-sampled color images (RB, GB, BB). For each of the three, the gaps are filled by interpolation – this is often called demosaicing. Inadequate demosaicing is one of the main causes of artifacts in color images, particularly near sharp edges.

An advanced camera will use its own complex interpolation algorithms for successful demosaicing. After the interpolation the data is tripled as there is now an R, G, and a B value for each pixel.

Further complicating the challenges, the demosaicing results in R, G and B values for each pixel, but the resulting image may still not appear exactly as the human eye would view the object directly. These values depend on:

- **Illumination spectrum**. Conditions vary, particularly in outdoor environments and have specific effects. For instance, there is more red present in morning sunlight and more blue present in the afternoon. The human eye automatically compensates for this, such that a white object looks the same regardless of the time of day/lighting conditions. White balance is the function that makes this adjustment in cameras. White balance is an automatic function in advanced cameras such as those from Adimec.
- **Object reflection spectrum**: Objects have a reflectance spectrum which is the portion of incoming light that it reflects over a range of wavelengths.
- **Camera** (or more precisely image sensor), **and Display spectral** sensitivity per color. Image sensors have an inherent spectral response. (Figure 5)

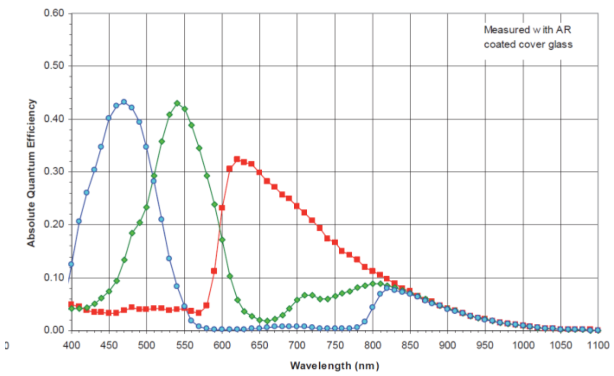


Figure 5: Quantum Efficiency of the Kodak KAI-01050 color sensor for blue, red, and green

This means for a given illumination spectrum, there are ratios of R, G, and B to then generate the full range of colors. The human eye also has similar curves as in Figure 5, but with different characteristics. Finally, the video display has its own attributes which must be compensated for.

Color processing is a sophisticated capability as developers try to deliver color recalculation that is optimized to bring human color perception from a screen-image as close as possible to color perception when looking directly at the actual scene. Adimec has created proprietary color recalculation algorithms which also include controls for saturation, protection from blur by interpolation, contrast enhancement and gamma. The end result is a crisp image with accurate color reproduction of the actual scene (Figure 6a-c for comparison).

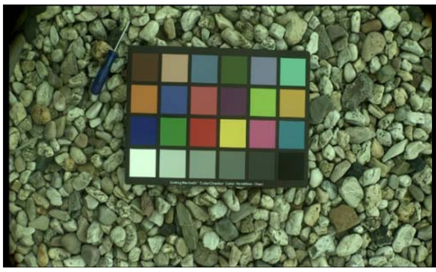


Figure 6a:
Camera image after demosaicing only

Figure 6b:
The effect of white balance on figure 6a. Note that the white square is now white

Figure 6c:
Final color image after applying color recalculation algorithm on the image in 6b

4. Design and Manufacturing for Repeatability and Reproducibility

The goal of the high-performance camera manufacturer is to design and implement well-built electronics that do not generate disturbances or add noise. The mechanical design not only involves the form factor choices, but also the critical procedures during manufacturing such as alignment, final testing, and EMC/EMI controls and assurances.

The design and manufacturing decisions are critical to the repeatability and reproducibility of the cameras as described further below.

Repeatability

Image uniformity can influence the accuracy of the system or the degree of closeness of measurements of a quantity to that quantity's actual (true) value. But the **precision** of a measurement system (or the degree to which repeated measurements under unchanged conditions show the same results) depends on repeatability and reproducibility.

A general definition of repeatability is the variation in measurements taken by a single person or instrument on the same item and under the same conditions. With respect to cameras, this refers to the consistency of a single camera to generate the same results despite changing conditions, such as temperature and time. The consistency of a camera not only reduces the down time of the overall system or additional software adjustments for the OEM, but also allows for more complex measurement algorithms.

For example, an important trend in inspection systems is the growth of 3D inspections, replacing either existing 2D inspections or introducing new inspection possibilities within production (e.g. 3D AOI pre-reflow inspection in Electronics Manufacturing). This results in more accurate information and numerical parameters to verify (intermediate) production step results and to better control both previous and next manufacturing processing steps.

Methods for 3D non-contacted measurements rely on optical inspection. In contrast to 2D imaging, 3D information in principle **requires acquisition of multiple images of a field of view** on the device under test. The consistency of images across the acquisition and processing stages is imperative.

Reproducibility

In general reproducibility is defined as the ability of an experiment or study to be accurately reproduced, or **replicated**, by someone else working independently. In the context of cameras, it is referred to as camera-to-camera consistency.

One method to ensure reproducibility is a mechanical process: very precise sensor mounting and alignment. The sensor can be positioned in six degrees of freedom (3 translational + 3 rotational) to guarantee that the active pixels are always in the same place (within certain well-defined tolerance ranges) with respect to the mechanics of the camera. A key to the accuracy and quality of results achieved in Adimec cameras is the attention to detail paid during the sensor mounting and alignment processes. In addition, each camera undergoes a rigorous, individualized assembly and test procedure process during which mechanical and electrical adjustments are made to ensure all cameras are consistent.

Thorough final testing to make every camera in a series as close to identical as possible allows for simpler tool matching, drop-in replacements, and automated set-up rather than complicated alignments each time

Not only is reproducibility critical to reduce system set-up time, it also helps with life cycle management by direct replacement. Nobody wants product changes or updates to create costly requalification of their system. In fact, without the proper life cycle management methods, change can be seriously disruptive. For example, medical equipment builders spend much time and money for FDA approval, and defense contractors must go through extensive qualifications. It is critical that product consistency is maintained as much as possible during the evolution of the product.

5. Interface Options

Camera manufacturers typically offer several interface connectivity options from the camera to the rest of the system to meet different needs. We have prepared a separate white paper discussing the pros and cons of different interface options:

http://info.adimec.com/camera-interface-overview-and-comparison-ePaper/

6. Summary

There are a wide range of factors, beyond the core image sensor, that need to be considered in the selection of a camera. While the image sensor is an integral component that has direct impact on the performance of the system, there are a variety of other criteria and features a savvy system developer should evaluate when choosing a camera supplier. Camera manufacturers make different design decisions that can have an impact on the resulting image. The camera producer can greatly enhance and augment the capabilities of the most leading-edge sensor, and provide the long-term security and ROI needed in an imaging system.

7. About Adimec

Adimec specializes in the development and manufacturing of high-performance cameras that meet the application-specific requirements of key market segments, including machine vision, medical imaging, and outdoor imaging.

Founded in 1992, the company partners with major OEMs around the world to facilitate the creation of industry-leading cameras.
Adimec's unique True Accurate Imaging® technology provides new levels of precision and accuracy to vision systems. Its diverse line of camera products meet a wide range of performance, size, cost, interface and application requirements.
Adimec has offices around the world focused on creating customer value and satisfaction through local, personalized support.