



WHITE PAPER
**COMPUTATIONAL
IMAGING**

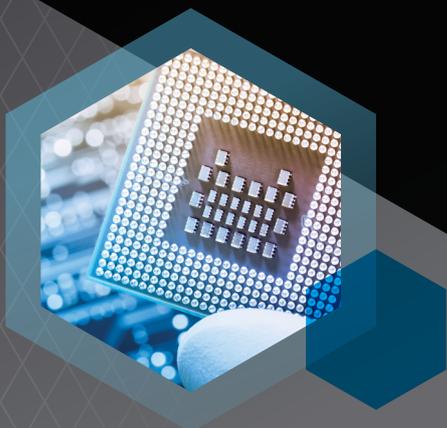
A multifunctional
imaging technique for
machine vision



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1. INTRODUCTION

The machine vision industry is a dynamic and continually evolving environment which embraces new techniques and new technologies to enhance the information that can be made available using imaging methods. It is well known that the wavelength and direction of machine vision illumination is critical in determining the information available in the image. How the light strikes the target determines how it will appear to the camera since the properties of the light allow different features to be highlighted. Computational Imaging (CI) makes use of this fact by using a multi-shot approach to acquire a sequence of images, each having different lighting or optical configurations. Data can be extracted from each image and combined to create an output image that contains details that are most relevant to the particular application. This is a versatile approach that, with an appropriate choice of lighting, optics and sequencing, can create many different imaging solutions by producing better images or images with unique characteristics. Typical examples include providing increased contrast, higher resolution color, multi-spectral features, extended depth of field, segmented 3D information, and combinational illumination.

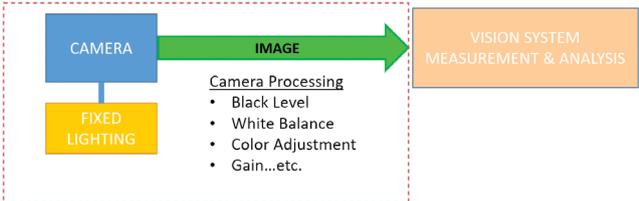
1.1 THE EVOLUTION OF NEW IMAGING TECHNIQUES

The evolution of new imaging techniques in machine vision is often made possible through the rapid advancements in image processing speeds and developments in CMOS sensor technology. Such developments enable techniques that have been known of for some time to make the transition into affordable and practical solutions that can

be used in real-world applications. Recent examples include 3D imaging (laser line triangulation, stereo, structured light, time of flight), polarization imaging and the use of different wavelengths, such as SWIR (Short Wave Infra Red), hyperspectral imaging and terahertz imaging. Essentially, however, all the techniques are seeking to capitalize on the different ways that light interacts with the target object.

1.2 AN OVERVIEW OF COMPUTATIONAL IMAGING

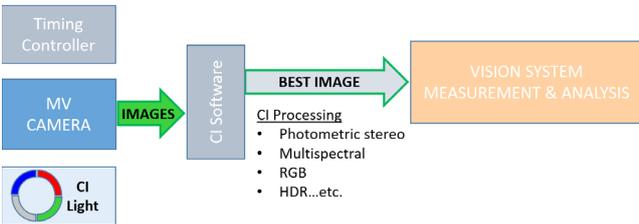
Traditional area scan imaging methods collect image data in a single exposure of the camera sensor with fixed lighting and optics. The resulting image can often require substantial post-capture image processing to highlight the features of interest, and yet still not produce the optimum image for subsequent analysis.



Traditional single shot image generation

The computational imaging approach has evolved from digital photography and is a multi-shot technique where programmable lighting and lens control systems are typically used to create image capture sequences that apply application-specific parameters such as illumination direction or angle, wavelength, intensity, polarization or focus.

The optimum components of each of these images is extracted in software and combined to produce a composite image of enhanced quality that contains information that is not available from a single image.



CI multi-shot image generation

This composite image can then be measured and analyzed in the normal way by a vision system. The essential components of a CI system are the lights, optics, multi-channel light sequencing hardware and CI software. Many CI tools have already been developed, to enhance contrast, provide ultra-resolution color, extend depth of field, extract 3D surface information, remove glare, combine well-known lighting techniques, and generate multispectral information in a single image. Since CI also works on moving parts, it offers new possibilities for creating solutions to difficult imaging problems in a wide range of machine vision applications.

1.3 WHY USE COMPUTATIONAL IMAGING?

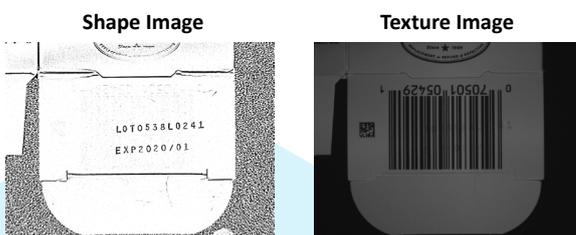
Producing high quality images, where the features of interest are displayed with good contrast and low noise is a fundamental requirement for machine vision. However, in many applications, producing such an image can be very challenging. The detail displayed in an image results from the use of appropriate illumination. Information that is not present in the image because of inadequate illumination can never be extracted using image processing if was not initially captured. Even if there is some information in the original image, extensive post capture processing can result in very noisy output images which may not be adequate for subsequent machine vision evaluation. Computational imaging aims to overcome these problems at the source by making use of different illumination combinations to ensure that the required detail is actually present within the image sequences for subsequent extraction. In this way improvements can be made in the final image quality and in some cases information can be revealed that would not be possible using other techniques. The following example of code inspection on a pharmaceutical carton is a good illustration.

Conventional Lighting



Carton flap imaged using conventional lighting in a single shot

While the conventional illumination shows both the UPC and date/lot code, they are superimposed, which would make it virtually impossible for both codes to be read by a machine vision system. Using the photometric stereo computational imaging method (described in more detail in Section 3.1) this problem can be easily overcome.



Shape and texture images from photometric stereo computational imaging

The carton flap is imaged sequentially using a 4-segment ring light. Photometric stereo algorithms are used to combine the 4 images to produce a shape image and a texture image of the flap. The shape image clearly shows the date/lot code and the texture image makes the UPC code readable. The use of computational imaging thus generates two images that can be read using conventional machine vision OCR techniques.

CI is an extremely versatile technique, since it can be used with a variety of configurations to achieve different results. It uses a multi-shot approach to create the new image and therefore in principle could be applied to almost any application where single shot imaging is used. It has already been demonstrated in the automotive, pharmaceutical, food, healthcare, packaging, electronics and wood industries for applications as varied as the identification of small surface defects, revealing overlaid text and barcode information, reading braille characters, improving color fidelity, highlighting pinholes in food packaging and imaging objects of different height in the same field of view. While the same light sequencing controller can be used for all of the CI techniques, practical considerations must be given to being able to choose the lighting and place it in the required position for the particular method being used.

There is a further benefit in that a number of CI techniques can be used in both 2D and 3D imaging systems. For example, Active EDOF (Extended Depth Of Field) extends the depth of field and improves object reconstruction in 3D imaging systems using structured lighting, by simultaneously refocusing the camera and the structured light projector at multiple planes. 3D HDR (High Dynamic Range) creates 3D structured light images with higher contrast ratios and less noise, allowing objects with specular, variably shaped surfaces to be accurately reconstructed.



2. COMPUTATIONAL IMAGING TECHNOLOGY

All CI techniques rely on capturing a sequence of images taken under different lighting or optical conditions and then extracting the features of interest from each image and combining them into the final image. A similar basic configuration is required to achieve this by all CI methods, although the specific components used will be dependent on the particular technique(s) being used.

2.1 IMAGE GENERATION

2.1.1 PROGRAMMABLE IMAGE ACQUISITION

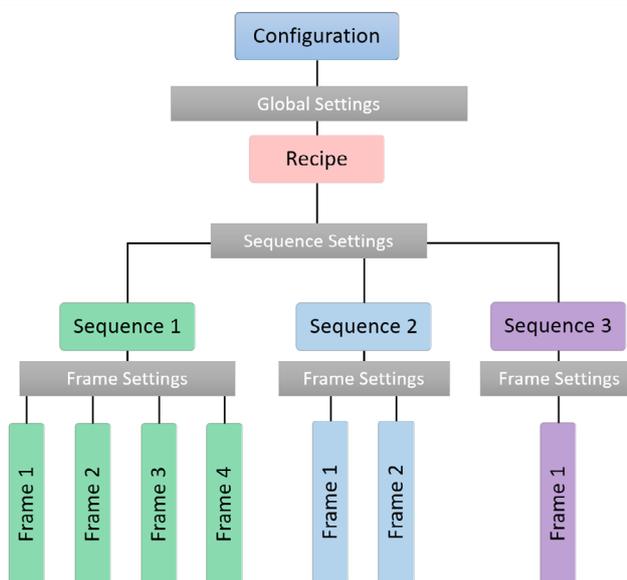
Programmable lighting and lens control systems are typically used to create image capture sequences that vary application-specific parameters such as illumination direction or angle, wavelength, intensity, polarization or focus. Whichever technique is used, it is essential that image sequences can be set up with the appropriate number of frames, frequency cycle and exposure time for the specific application. Image sequencing hardware must generate reliable and repeatable sequences so that consistent images are generated for the computational process.

2.1.2 DIFFERENT CONFIGURATIONS FOR DIFFERENT APPLICATION TYPES

There are a number of different CI techniques and they use different light types and geometries and different software for the generation of the final image. For example, Photometric Stereo uses lighting from four or more directions to cast a directional shadow around raised or pitted features on the target. The illumination may be a ring light with four 90° quadrants, an array of four bar lights or any other arrangement that produces directional lighting. For ultra-resolution color imaging, a full color ring light with 3-channel control of red, green and blue output is used in conjunction with a monochrome camera to create a sequence of 3 monochrome images corresponding to the RGB components of the image. More configuration details for the different CI techniques can be found in Chapter 3.

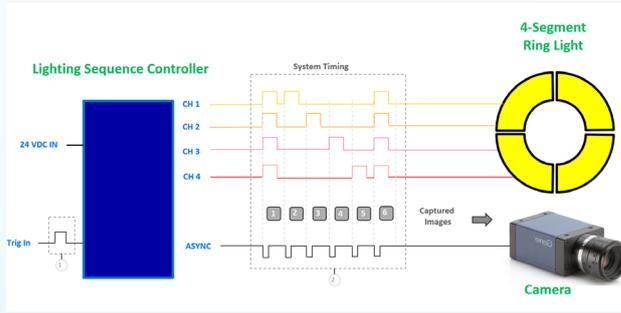
2.2 LIGHT SEQUENCING HARDWARE

At the heart of all CI techniques is a programmable controller designed to create and manage the lighting sequences for image capture. The LSS-2404 Light Sequencing Switch from CCS Inc. is an excellent example of this. It can be used both with small precision lights or large, high output lights for large area inspections, covering all Fields of View. It acts as a mini enhanced PLC and specifies one synchronous light pulse (or liquid lens refocus) together with an image acquisition in a single frame, allowing highly flexible and powerful sequencing. Multiple frames can be combined to form a sequence, and multiple sequences can be combined in a recipe or job file.



Programming Sequence

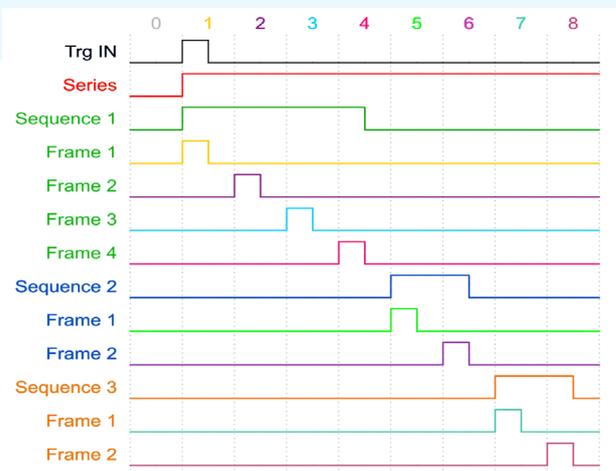
This controller has a 4-channel output. The diagram shows a timing diagram for Photometric Stereo CI.



Typical timing diagram for Photometric Stereo image capture

The diagram shows operation in an auto sequence mode. A single trigger to the controller starts the sequence. The sequence and timing are generated automatically. A strobe pulse is sent out on each lighting channel along with a synchronized trigger to the camera. The controller automatically indexes through the frames in a multi-frame sequence; for Photometric Stereo four frames are needed if the part is stationary and five or six frames if the part is in motion. In the example above, a total of 6 triggers and captured images is generated.

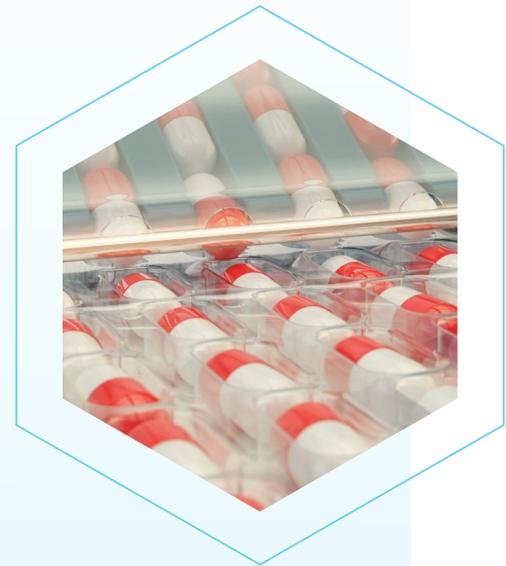
The controller can be operated either as a master or a slave. When acting as a master, the controller sends triggers to the camera and light in the programmed sequence once it receives one trigger from the sensor/machine.



Recipe execution

Here a recipe is operating from a single trigger. When it is triggered, it runs all sequences; the frames within a sequence and the number of times a sequence is programmed to repeat. Once the recipe execution is completed, another trigger is required to initiate it again.

When acting as a slave, the controller receives a trigger from the camera/sensor/PLC and then triggers the light



for one frame. This means that it will require multiple triggers to execute an entire sequence or recipe. The controller is supplied with an API for programming as well as a GUI in order to provide a choice of how to configure and control CI.

2.3 CAMERA TECHNOLOGY

Any camera that can send/receive triggers can be used for CI. A GenICam compliant camera (typically GigE Vision or USB3 Vision) is recommended, but not required. All current CI techniques use monochrome cameras, typically with resolutions of between VGA (0.3 MPixels) and 5 MPixels. Higher resolutions are not usually advantageous due to the limitations on throughput. In addition, the smaller pixels found in higher resolution cameras may have too much noise for effective image processing. A smaller image or using a Region of Interest (ROI) from a larger image is recommended to reduce the number of pixels in order to achieve a higher processing rate when merging the images. If a higher resolution camera is used, reducing the resolution in the camera configuration software is an effective way to increase throughput (e.g. reduce a 12MPixel image to 2-3 MPixels). There is no minimum frame rate required for the camera. However, since multiple images must be captured and the inspection cycle time is typically the same as for single-shot imaging, cameras with higher frame rates are often useful. Cameras with large image sensors (above 1 inch format) can be more difficult to pair with lenses and are not generally recommended for use with CI. In addition, many applications benefit from using low distortion or telecentric lenses to remove optical distortion and parallax error.

2.4 IMAGING MOVING COMPONENTS

Many CI techniques can also be performed on moving objects, meaning that they can be applied in a production line environment. Naturally, the camera field of view (FOV) must be set to be large enough that the part stays within it during the entire capture sequence. The use of global shutter cameras is particularly important for moving part applications, since the images must be precisely aligned



for motion correction and for proper image merging. In practice, one or two additional images are needed to track the part for proper registration as it moves past the camera. Typically, pattern matching techniques are used to precisely locate the part in two or more frames of the capture sequence. To avoid complications, the part should move straight at constant speed and not vary in size (e.g. not down an inclined plane).

For 2D applications in a single focal plane such as Photometric Stereo, optical distortion is the biggest source of error for motion correction. The use of a lens with very low distortion (0.3% or lower) is recommended. For 3D applications involving depth range, such as Extended Depth Of Field, telecentric lenses will work best in most cases to minimize perspective distortion. If regular lenses are used, longer focal lengths and greater working distances are recommended to minimize distortion (50 mm or greater).

2.5 CREATING CI IMAGES

Key to the outcome of CI is the ability to combine the multi-shot images to create a single enhanced image for subsequent processing and/or measurement by the vision system. This can either be done using commercially available software packages or using an SDK.

2.5.1 COMMERCIALLY AVAILABLE SOFTWARE

Software support is available through leading machine vision suppliers - including Cognex, Matrox, MVTec, Teledyne Dalsa, Silicon Software, National Instruments, Omron and Datalogic. Computational imaging techniques such as Photometric Stereo, HDR, Ultra-Resolution Color and Extended Depth of Field are either available directly through these imaging software manufacturers or can be programmed from the included vision tools. They allow vision system builders to choose a process to get the most beneficial image for their application at hand. In general, the software is run on a PC, but may also be available in some smart camera environments.

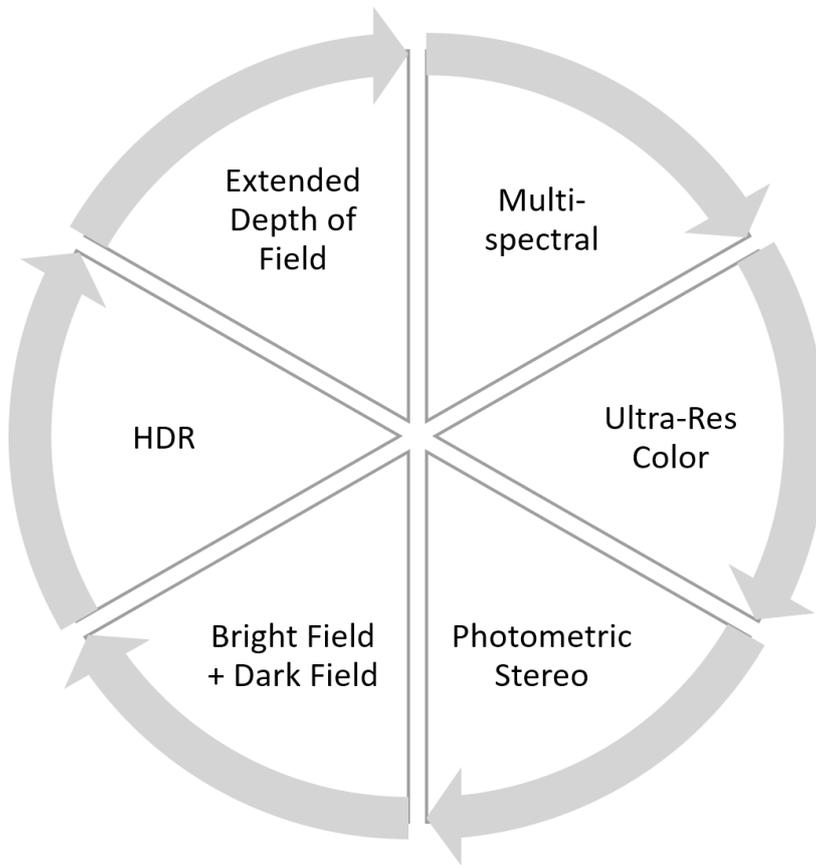


2.5.2 CI SDK

OEMs, system integrators and machine vision developers who wish to build the Computational Imaging tools into their own dedicated application software can make use of a software development kit (SDK) that is supplied free of charge with the LSS-2404 Light Sequencing Switch. This SDK contains an extensive set of CI tools. It is available in both C# and C++ versions and is compatible with the leading machine vision software development packages. The camera software must be capable of passing a pointer to the captured image to the CI SDK.

The basic principles of operation described above can be applied in a variety of different ways, offering a number of different imaging techniques. These can all provide powerful alternative and highly effective solutions to many practical problems encountered in machine vision applications. This versatile approach means that in addition to the methodology already available, system designers can think in new ways to solve challenging imaging problems.

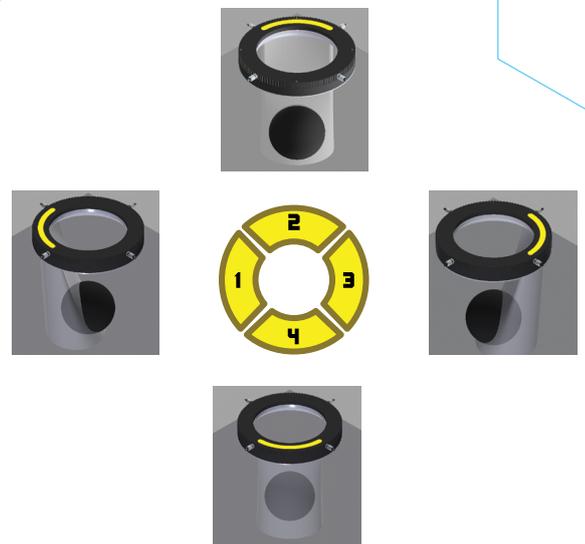
3. COMPUTATIONAL IMAGING TECHNIQUES



Computational Imaging Techniques

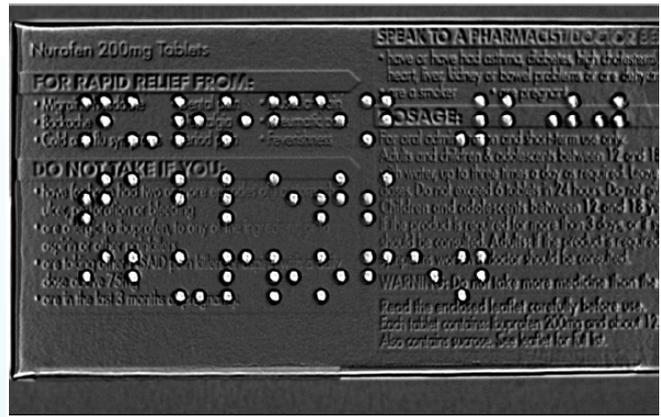
3.1 PHOTOMETRIC STEREO (SHAPE FROM SHADING)

Photometric Stereo, also known as ‘Shape from Shading’, is a technique used to separate the shape of an object from its 2D texture or surface coloring. Typically, it is used to highlight 3D surface features or imperfections in one image, known as the shape image, and remove glare from highly reflective parts, known as the texture image. In general, the object is sequentially illuminated from 4 different directions, typically using a ring light with four 90° quadrants or an array of four bar lights or any other configuration that produces directional lighting.

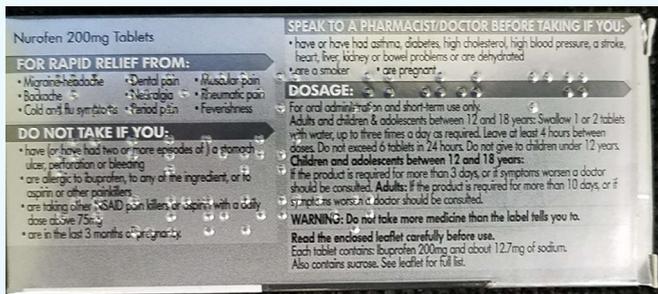


Sequential 4-quadrant illumination for Photometric Stereo imaging

The shape from shading software processes the four images to generate the shape and texture images. The shape image is produced by removing all contributions from the source images that are the same, which leaves the differences created by shadow. This enhances 3D surface details such as scratches, dents, pin holes, raised printing, or engraved characters. It is especially effective on surfaces that have 3D structure but little to no contrast. The texture image is produced by removing areas in the images that are different (the light coming from each direction). This removes interference from the surface structure and removes glare. The following example shows how Photometric Stereo can be used to extract braille information from a pharmaceutical package for reading.

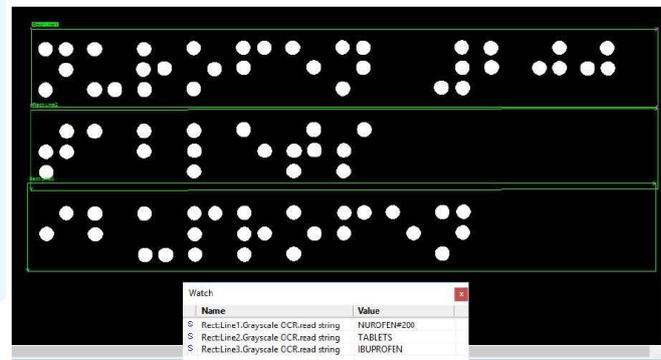


Shape image from Photometric Stereo



Original image of package

The text can then be compared to the original text on the package.



Final processed image

In the image of the pharmaceutical package shown above, the braille characters can only be partially discerned.



The four source images for Photometric Stereo

From the four directional images of the package shown above the Shape image can be generated using shape from shading algorithms.

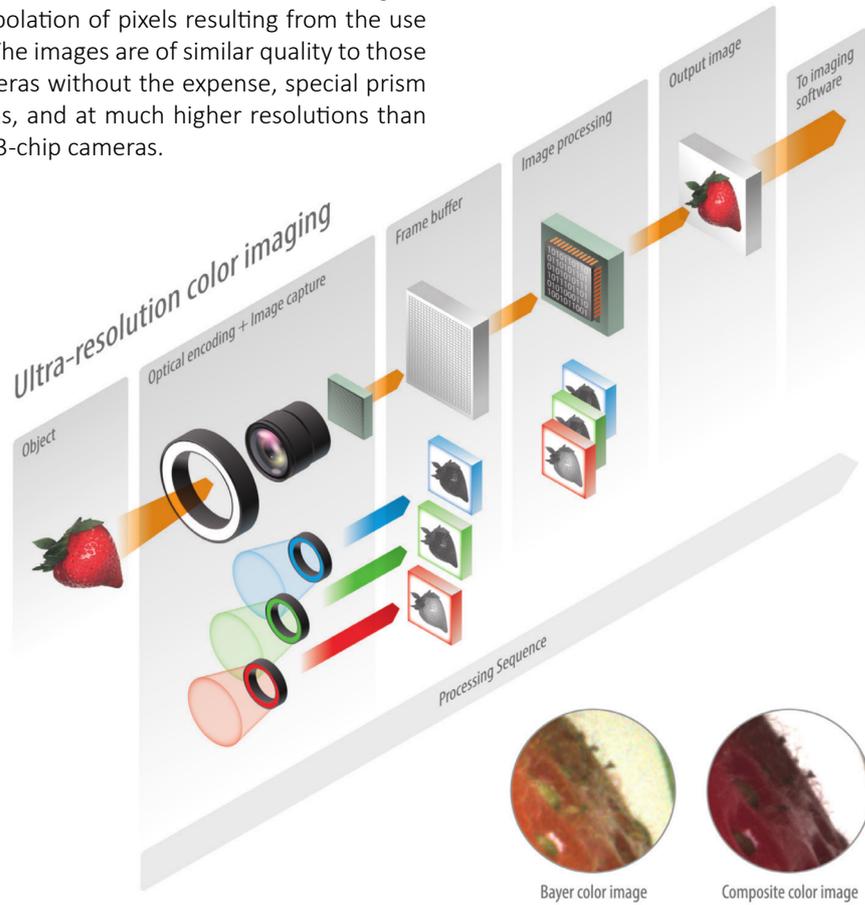
The computed shape image reveals the braille characters. This can then be further processed using standard machine vision techniques including object segmentation (blob analysis). The resulting imperfect dots can then be converted into perfect dots for reading by OCR methods.



3.2 ULTRA-RESOLUTION COLOR IMAGING

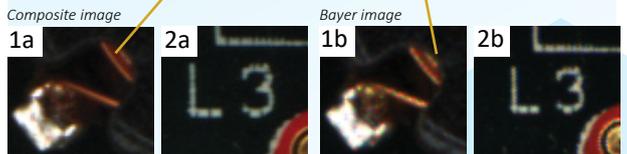
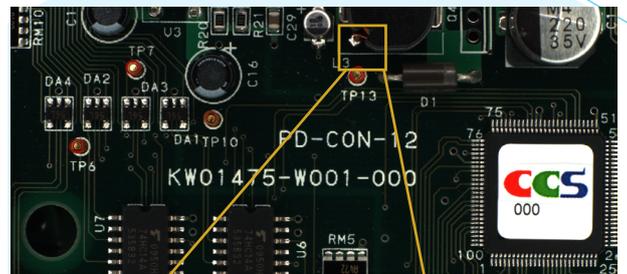
Ultra-Resolution Color imaging is a technique which uses RGB lighting and a monochrome image sensor to create high resolution composite color images. Composite color images are much sharper than those produced by a single image capture with a Bayer or mosaic color camera, since every pixel on the sensor is used to form the image – there is no interpolation of pixels resulting from the use of a Bayer filter. The images are of similar quality to those from 3-chip cameras without the expense, special prism or lens limitations, and at much higher resolutions than that of available 3-chip cameras.

With the proper hardware, ultra-resolution color imaging can be achieved at practical data rates. For example, using a 12 MP CXP4 type monochrome camera with CXP4 frame grabber, the camera can run at 180 fps at 12 MP in 3 frame sequences (R,G,B), with the full color light sequentially strobing R, G, B. The output of this process is a 24-bit 12MP full color image at 60 frames per second.



A full-color ring light with 3-channel control of red, green, and blue output and a monochrome camera can be used to generate a sequence of 3 monochrome images using the red light, green light, and blue light respectively. These images can be aligned and a composite color image computed from the ratios of the grey level values of each of the equivalent pixels in the three images. Proper white balance can be achieved by scaling each color channel while imaging a neutral white target.

In this way, the three 8-bit monochrome images are combined to form a 24-bit color image at the full resolution of the sensor. The benefits of having the full resolution available in the composite image are further highlighted when the image is digitally zoomed for higher magnification inspection. Edges appear much sharper, contrast and color are improved and noise is reduced compared to an equivalent Bayer image. In addition, other artifacts such as red and green aliasing are eliminated.



From the top: A sequence of monochrome images from red, green, and blue light. Using these, a color image is computed. Below is a comparison of fine detail between the ultra resolution color imaging and a Bayer imaging

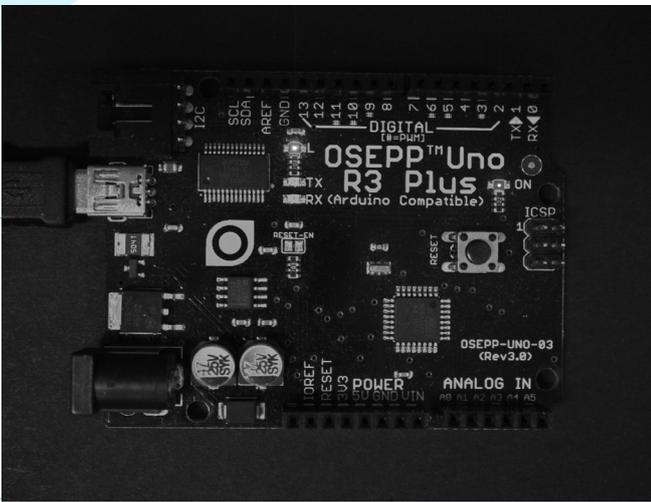
3.3 HDR (HIGH DYNAMIC RANGE IMAGING)

This technique is used to create images where extremes in contrast are removed to produce a more evenly lit image. The dynamic range of an image defines the ratio of the brightest object to the darkest object that can be distinguished in a single image. However, many machine vision scenes contain extremes of contrast that exceed the normal dynamic range. In these cases, if the camera gain or exposure is reduced so that the brightest areas can be imaged properly then other areas will be too dark. Conversely, if the gain or exposure is increased to image the dark areas then the bright areas become saturated. CI can solve this by the acquisition and combination of a series of images produced using different illumination levels. This is achieved by creating a sequence of images using illumination with different strobe widths.



PCB illuminated with short, medium and long light pulses respectively

The short light pulse is set to provide detail on the brightest areas of the image (the lit LEDs), while the long light pulse is set to give details on the darkest part of the image.

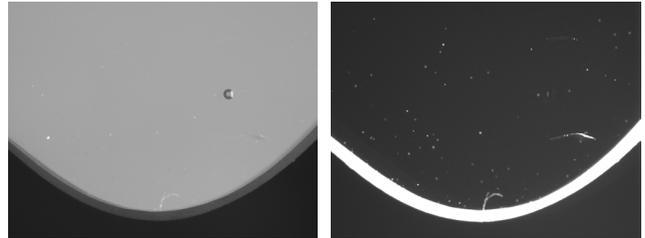


Computed HDR image

The properly lit parts of each source image are combined to form a single image with higher dynamic range. This method can be used with any illumination source. It is a powerful alternative to varying the camera exposure to produce HDR images. Using long camera exposures for the darker parts of the image can introduce noise into the composite image.

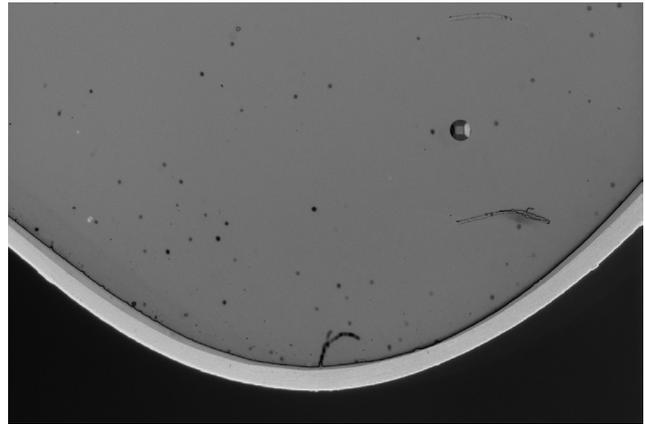
3.4 BRIGHT FIELD/DARK FIELD IMAGING

This CI method combines the advantages of two well-established, but different lighting techniques to display features created by both methods in a single image. Bright field (coaxial) and dark field (low angle) illumination tend to reveal different types of information about an object. In particular, dark field imaging highlights surface information such as scratches, pits and microscopic particles.



Bright field and dark field images of oil drops on a scratched glass plate

Using CI techniques, images can be obtained using the bright field and dark field sources and combined into a single composite image. Here the bright field image shows the droplets and larger particles but not the surface detail.



Composite bright field/dark field image

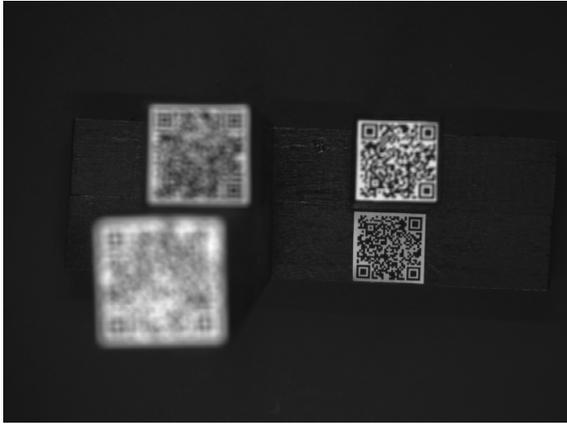
The composite image shows the surface details in addition to the droplets and larger particles. This approach could be applied to any combination of lighting that produces different types of detail in the individual images.

3.5 EXTENDED DEPTH OF FIELD

A common difficulty experienced in machine vision applications is insufficient depth of field when imaging objects of different heights or at different distances from the lens. A common solution to this problem is to stop down the aperture, but this severely reduces the amount of light reaching the image sensor, leading to noisy images, especially on moving components. In addition, resolution is lost at narrower lens apertures. CI can be used to overcome these issues and produce an extended depth of field by using a liquid lens or a multispectral light source, among other techniques.

3.5.1 LIQUID LENS APPROACH

Since liquid lenses can be refocused in milliseconds through the application of an electric current, a sequence of images can be produced where for each image, the current from the liquid lens controller is set to the appropriate focal point for one component of the image.



Single shot image of 2D codes on labels with an overall depth range of 14"

The four individual images each have one of the labels sharply in focus. These 'in focus' parts of each image can be combined to form a composite image with all of the labels in focus simultaneously.

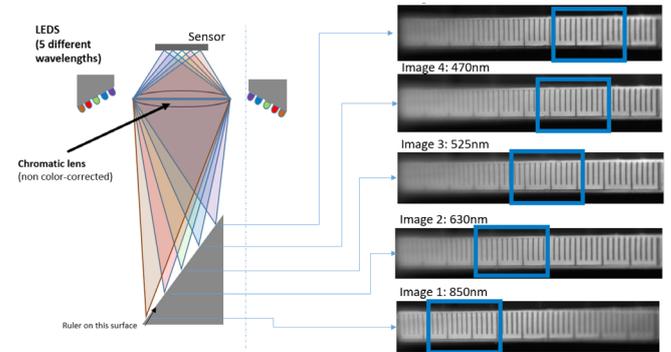


Fully focused composite image

This approach avoids both loss of light and resolution and can be performed using any light source. For 3D applications with a depth range, telecentric lenses will work best in most cases to minimize perspective distortion. With regular lenses, using longer focal lengths at greater working distances is recommended, to minimize distortion (50 mm or greater).

3.5.2 MULTISPECTRAL LIGHT SOURCE

A lens that is not corrected for chromatic aberration will focus different wavelengths at different working distances and this can be used as the basis for extending depth of field. The object is imaged sequentially using multiple wavelengths, possibly extending from the UV to NIR depending on the application. The image for each wavelength will have a different portion in focus.



Multi-wavelength imaging of inclined ruler

As above, the in-focus part of each image can be combined to form a fully focused composite image.

3.6 MULTISPECTRAL IMAGING

Multispectral imaging can also be used in CI to create a sequence of images containing wavelength-specific information that can be combined into a composite image to simultaneously display the important features. Typically this works best when the features of interest are visible in the UV, visible and IR spectral regions.



Foil package image sequence with white light, NIR and UV

In the example given here, the visible region is being used to inspect print on foil packaging, the UV is needed to see dye marking and NIR light can help to see pinpricks and other foil breaches through the print. Using a weighted filter, a single composite image can be created to display the information from each spectral region.



Composite image, together with a pseudo-colored version

Although the output image will be monochrome the application of pseudo-coloring highlights the contrast between the print, UV dye and pinprick holes.

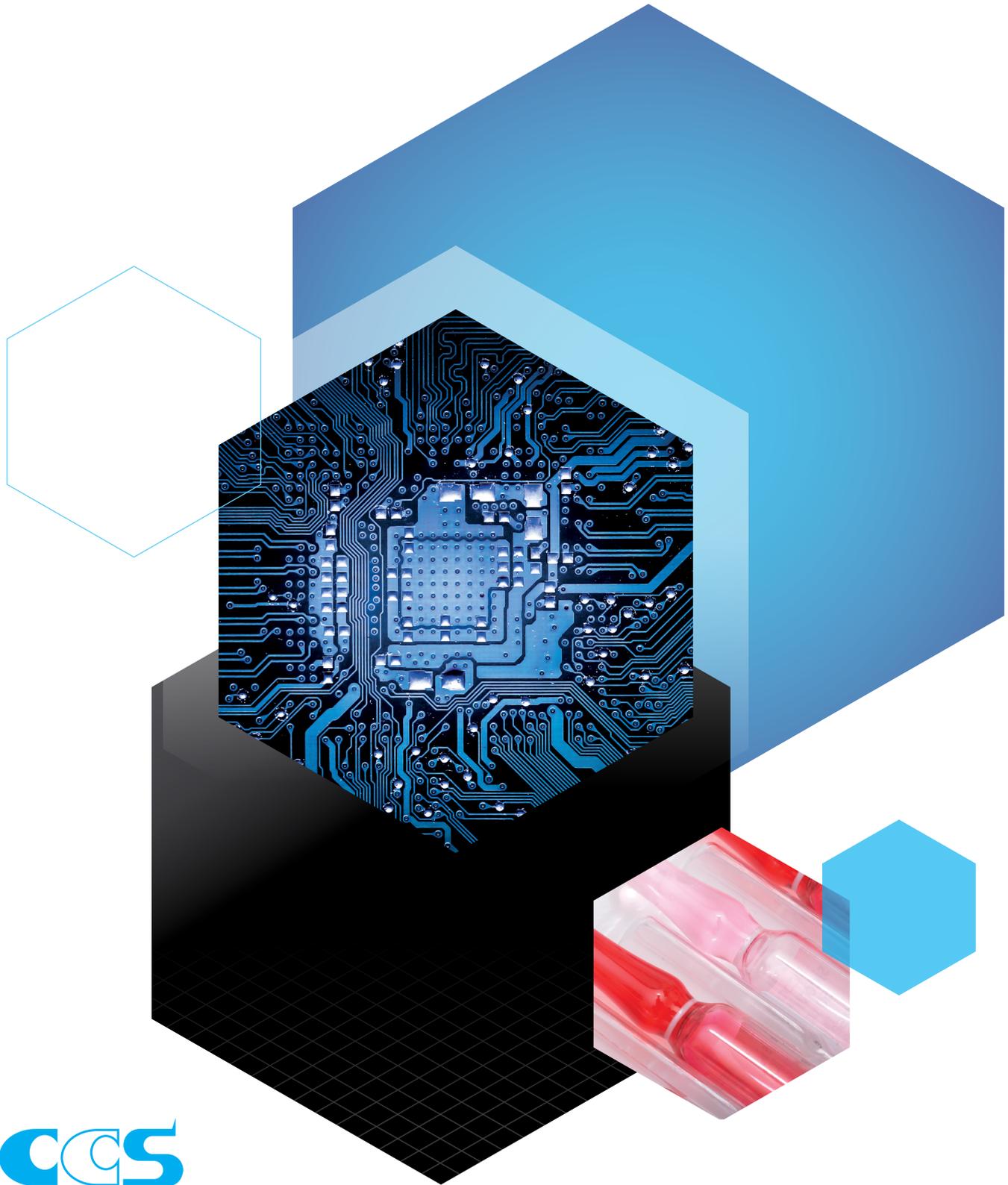
4. SUMMARY

The basic principles of Computational Imaging, with its multi-shot approach, can be applied to many different lighting and optical configurations to deliver a wide range of alternative imaging methods. It should also be noted that these techniques need not be mutually exclusive. Provided that the correct configuration of lighting can be set up, the system could be programmed to run a number of different CI sequences. So, for example, multispectral imaging and photometric stereo imaging could be performed consecutively on the same component.

With its benefits to both developers and users, Computational Imaging technology is becoming increasingly prevalent in the machine vision industry and machine vision manufacturers are responding to this trend with compatible hardware and software. The technologies that enable CI (fast CMOS sensors, high speed interfaces, cheap computing power) will continue to improve and further accelerate adoption of CI technology.

Computational Imaging provides a powerful solution to many of the challenges found in machine vision, and although it is not intended to replace single shot imaging, it is expected that new variations based on the same basic principles will continue to emerge.





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