Imaging Design
Benchmarking

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INTRODUCTION

One important activity in developing a vision system is to validate its implementation meets the engineering objectives. Two characteristics of a successful vision application are how long it works without needing the attention of a vision engineer and how straightforward it is to maintain and to duplicate. A critical step to achieving all four of these objectives is benchmarking the vision system.

In the context used here, a benchmark is a measure or indication of a desired operating characteristic. Within the scope of this paper there are two areas that should be benchmarked:

- Imaging (camera and lens)
- Illumination

Imaging benchmarks are independent of the image processor and its software. That is, they can be performed independently of the features of most vision systems and their programs except that it must be possible to acquire and store images for off-line analysis.

When a vision system is first developed, the vision engineer performs tests to ensure the components perform as expected. These tests allow the vision engineer to establish benchmarks that verify the vision system’s performance at the time it was ready for commissioning as well as for future reference.

When a vision system undergoes maintenance, the technician can make new observations and compare them with the established benchmarks. This enables the technician to identify whether or not significant changes have occurred and where they occur so appropriate corrective action is taken if necessary. It also eliminates the need for the technician to try a change to see if the vision system performance improves. Such blind changes of a vision system can lead to serial degradation that requires a vision engineer to correct. But without benchmarks, even the experienced vision engineer cannot be sure the vision system is returned to its original operating condition.

Benchmarking does require access to specific tools like test patterns. Some of these tools may be application specific while others may be more generic. Benchmarking is not a process to facilitate adjustment or calibration; those functions must be performed before benchmarking. Since benchmarking is not calibration, it does not require traceability to international standards, and the tools can be purchased or created by available technology (e.g., a laser printer) without the need for traceability. However, the tools must be of suitable materials and maintained in such a way that they
do not deteriorate or change over the service life of the vision system. Maintenance of the benchmarking tools adds additional responsibility on the vision system’s team.

Finally, benchmarking a vision system is not about precise quantitative data, but about data that can establish the characteristics of the vision system well enough so that if those characteristics are reproduced, the vision system can be expected to perform as well as when the benchmarks were recorded.

Benchmarking the imaging provides data on the following characteristics:

- Critical imaging dimensions
- Camera settings
- Lens settings
- Illuminator settings (if any)
- Imaged field-of-view
- Imaging (optical) resolution
- Depth-of-field
- Illumination intensity
- Illumination direction
- Illumination uniformity
- Color
- Image distortion
- Image noise
- Illumination polarization (if used)
RECORD THE SETTINGS

The vision system’s settings must be recorded as a prelude to benchmarking. This includes important mechanical dimensions related to imaging as well as the position of all adjustments and accessible parameters. It is critical that these values be the ones actually used in the vision system’s operation when viewing product.

Imaging includes the illumination, the camera, and the lens adjusted as they work best for the application. Benchmarks for imaging require the acquisition and storage of unprocessed images. Almost all vision systems support this capability.

Typical settings that should be documented are:

- Measured 3D position of the light source relative to the field-of-view
- Working distance from the field-of-view to the lens
- Lens aperture setting
- Lens focus setting
- Lens focal length setting (if using a zoom or varifocal lens)
- Camera gain
- Camera exposure time
- Camera frame rate (if applicable)
- All other programmable camera settings even if factory defaults
- Illumination power level (if adjustable)
- Illumination pulse width (if pulsed illumination is used)

When benchmarking is used to insure reproducibility, either for replication of the vision system or component replacement on an existing vision system, allowances need to be made for the fact that there are variations in components. Two cameras of the same make and model can exhibit differences in sensitivities. These differences may require a change in the camera’s gain, its exposure time, or in the output of the illuminator.

The effective focal length of two lenses of the same make and model can vary slightly, typically less than 3%. This change in effective focal length may change the size of the field-of-view. Either the size change must be tolerated, or the camera’s working distance changed to achieve a precise field-of-view.

The light output of an illuminator will vary from unit to unit depending on, say, the particular group of LEDs used in the source. If the light source has an adjustment for its light output, this can be changed to bring the imaging performance back to its benchmarked status.
BENCHMARKING THE IMAGE BRIGHTNESS

Since the cameras vary in sensitivity and light sources vary in light output, it is very desirable to benchmark the image brightness. The image brightness is best documented using an intensity histogram with a single exemplary part in the field-of-view. For future benchmarking, the same part should be used if it is possible to store and preserve it so that its reflectance does not degrade (e.g., oxidation from the atmosphere).

When reproducing a system, the intensity of the new system should be made to match the histogram of the benchmarked system. It may be necessary for the vision engineer to decide whether to change the illuminator output, the camera gain or exposure, or to accept the difference. With modern machine vision algorithms, performance can remain reasonable consistent if the brightness of the image varies somewhat as long as no critical pixels are going into saturation.

It should be noted that changing the lens’ f-number, although an obvious and very easy option to get the intensity histograms to match, is not advisable. Although changing the lens aperture does affect the lens’ light gathering power and thus the intensity histogram, it also changing the lens’ depth-of-field and the lens’ resolving power. Maintaining depth-of-field and optical resolution are typically more important that slight changes in the intensity histogram level.

For a color vision system, the intensity histograms for each of the three color channels, typically red, green, and blue, should be acquired and archived.
The two characteristics recorded in this benchmark are the size and the position of the field-of-view. The size relates to actual magnification, and the position relates to camera/lens pointing.

To benchmark the field-of-view, a target must be positioned so it is centered in the intended field-of-view. The target can be anything that facilitates observation. It can be as simple as a scale, or as sophisticated as a calibrated target, or a project-specific target produced on a laser printer. The important requirement is that the target can be positioned in the exact same location every time the system is benchmarked. This may require some early thought about fixturing in the vision system design.

Record and save the image and also the size and position dimensions as read from the scale or target.

In evaluating the field-of-view dimension keep in mind the tolerance on the effective focal lengths of most lenses is around ±3%. Therefore, in replicating a vision system, there will likely be a small difference in the size of the actual field-of-view.
Figure 4 – Project Specific Field-of-View Target

111.3x83.5mm
Optical resolution at the system level is the detail that can be resolved in the image. It is dependent on the camera’s image resolution (rows and columns of pixels), on the size of the pixels on the image sensor, and on the lens’ optical resolution. Often optical resolution is specified on the image, but for application purposes, the resolution will be evaluated where it is most important: on the scene.

The typical technique for benchmarking resolution is to place a resolution target, such as the USAF resolution target, in the center and in all four corners.

Since most commercial resolution targets are designed for very high resolution, it may be necessary, on occasion to make your own project-specific target using a laser printer. Remember, though, the paper from a laser printer is not dimensionally stable. However, the file from which the print was produced will stay dimensionally stable and should be saved with other project information. For such a target for benchmarking purposes only, the target needs to have only three sets of parallel bars: one for the expected resolution, one for slightly coarser resolution (nominally 1.15 times the expected resolution), and one for slightly higher resolution (nominally 0.85 times the expected resolution). The bars in the corners must be oriented in both directions for the reasons explained below.

For example, if your target resolution on the scene is 4 line-pairs/mm, then each dark and white bar should be 0.125mm wide at the target resolution. For the coarser resolution, each dark and white bar will be 0.144mm wide, and for the finer resolution target, each bar will be 0.106mm wide.
In the middle of the field-of-view, it is usually only necessary to note the resolution with the bars oriented in one direction. However, at the corners of the field-of-view, it is necessary to record the resolution both with the bars oriented toward the center of the field-of-view (the tangential direction) as well as with the bars oriented 90 degrees from the previous orientation (the radial or sagittal direction). At the corners, the lens' resolution is different in each of these two directions.

Having a only three sets of bars limits the target to verifying that the resolution is met, it does not establish what the imaging's limiting resolution is. A commercial target such as the USAF target has a wide range of bar widths and can be used to find the limiting resolution.
BENCHMARKING THE DEPTH-OF-FIELD

When benchmarking the depth-of-field it is very important that none of the imaging parameters be disturbed. This includes the lens’ focus, the lens’ aperture, and the camera’s height (lens working distance).

There are two methods of benchmarking the depth-of-field:

- Inclined scale
- Elevated target

INCLINED SCALE

The inclined scale can be a ruler or scale inclined at a known angle from the field-of-view. The range in the image in which the graduations appear in sharp focus gives the depth-of-field range. While a scale is commonly used, it is possible to make or purchase (from, for example, Edmund Industrial Optics or Max Levy Autograph) a depth-of-field gauge. The commercially available depth-of-field gauges are usually easier to fixture in place than an inclined scale or ruler.

Figure 7 -- Ruler at an Angle Showing Depth-of-Field
ELEVATED TARGET

A target, such as that used to verify resolution is imaged at the nominal working distance as well as the near and far limits of the required depth-of-field range. This usually requires the design and construction of fixturing to insure reproducibility of results. Alternatively, something like a lab jack can be used to move the target vertically to the desired heights.

Depth-of-field is valid if the required resolution is achieved at the limits of the required depth-of-field as well as at the nominal height. It is possible for the depth-of-field to extend far beyond the required range. The technique of using an elevated target is difficult to use to actually measure the total range of the depth-of-field.
BENCHMARKING ILLUMINATION INTENSITY

Illumination intensity can be benchmarked in one of two ways:

1) Using a calibrated light meter
2) Using the installed camera

The advantage of using a light meter is that the measurement is calibrated (usually to ±10%). The advantage of using the machine vision system’s camera is that you are insuring repeatable illumination even though sensitivity varies from camera to camera. The light meter method may be impractical for very small fields-of-view such as those for a microscope.

The procedures are different for front lighting and backlighting.

LIGHT METER, FRONT LIGHTING

Measure incident light energy on the scene. The light meter’s sensor is placed at the center of the scene, and the value of the light measured is read out. The light meter usually reads in lux – lumens per square meter of incident light energy. The disadvantage of this method is that for most vision applications, the meter’s sensor is picking up incident light in only a small part of the field-of-view, and its reading might be affected by non-uniformity of the illumination. It is extremely important that benchmarking provide a way to position the light sensor reproducibly; either by a fixture or by careful measurements.

The light meter method is not applicable for very small fields-of-view such as those using a microscope.

LIGHT METER, BACKLIGHTING

In this case, the light meter’s sensor is placed just in front of the camera’s lens. While the meter will still read in lux; the more correct reading would be in candelas (lumens/steradian), but this measurement reading is not facilitated by most light meters.
CAMERA, FRONT LIGHTING

The second method of measuring intensity is using the vision system’s camera. The camera is not a calibrated sensor – two cameras of the same make and model will have different sensitivities. So the measurement is relative. However, the goal is to get the exposure right; so, using the vision system’s camera for the measurement supports one part of the primary objective – knowing that the imaging setup meets its requirements. It does not, however, insure that the imaging setup can be reproduced. See “Benchmarking the Image Brightness” above.

Preferably, you cover the field-of-view with a target of uniform reflectance. For most methods of illumination, this target should be diffusely reflective. Some examples of useful materials are photographic gray card (18% reflectance on one side and 90% reflectance on the other) or a sheet of magnesium oxide, barium sulphate, or other materials sold by among others, Labsphere. For very large fields-of-view, it may be necessary to resort to backgrounds of paper or cloth, but it is impractical to expect the manufacturers of these products to control the reflectance of their products, and reproducibility of the measurement is compromised.

There are occasional situations where the vision system is intended to image specularly reflected light. For those cases, the use of a diffusely reflecting background may not provide a satisfactory method for benchmarking intensity. If the object is planar, then the background can be a flat mirror of appropriate dimensions. If the object being imaged is a more complex shape, it may be difficult to benchmark intensity except by using a diffuse background. It is very important that the light source intensity not be altered from its operational level for benchmarking. If necessary, neutral density filters can be used over the camera’s lens or the exposure time of the camera can be adjusted during the benchmarking to give adequate exposure.

It might be argued that having an actual “gold standard” part in the field-of-view would work. However, for the benchmark to be repeatable, the both the gold standard part and any objects in the background must be constant over time. This may be difficult to achieve.

Once the background is in place, capture a image of the scene with the illumination set and the camera’s parameters set as they are used for the vision application. Have the vision system calculate and report the maximum and the average gray level for the scene. You must make sure the maximum gray level reported by the vision system is not the maximum available to the vision system (e.g., for a vision system with 8 bit pixels, the maximum reported gray level cannot be 255). If the maximum possible gray level is reported, that indicates the camera is in saturation, the maximum reading is invalid, and the average gray reading is compromised. With few exceptions, it is not desirable to have the camera operate in saturation. If it is, then reduce the intensity of the light source or use a
background material with lower reflectivity. The average gray value is the benchmark for the illumination intensity.

**CAMERA, BACKLIGHTING**

In this situation, have the camera image the empty scene directly and report both the maximum and the average gray level off the image. Again, it is normally undesirable for the camera to be in saturation. There are instances where the intensity of the backlight will, by design, be set to saturate the camera. In that case, the camera’s exposure must be reduced to below saturation. The preferable technique is to use a neutral density filter in front of the camera’s lens. It is also possible, but slightly less desirable, to reduce the camera’s exposure by using a faster shutter speed (shorter exposure time) if that is facilitated by the vision system.
Illumination direction is benchmarked, at least for front lighting, by the use of a polished sphere placed in the field-of-view. In actuality, a polished half sphere would be better, but those are somewhat unusual. Often the sphere is a polished steel ball available from bearing suppliers. It can also be a decorative tree ornament, a half-round automobile hubcap (i.e., dog dish hubcap formerly very popular on customized automobiles), or a gazing ball popular for gardens.

The ball is placed in the field-of-view. A bit of modeling clay placed discretely can be used to secure it from rolling. However, an even more preferable way of fixturing the ball is to create a black anodized aluminum plate with the ball press fit into the center of the plate. The plate facilitates fixturing the ball in the center of the field-of-view.

The image of the illuminated ball shows the direction the illumination is coming from. Capturing and archiving the image provides a benchmark for others to use to check the vision system or to reproduce the vision application.
Figure 13 – Dog Dish Hubcap

Figure 14 – Tree Ornament

Figure 15 – Gazing Ball
A single point of reflected light indicates a single point source. If the light is centered on the ball, it is on-axis illumination.

When more than one point source of illumination is used, the polished sphere will show multiple points – one for each source.
For ring lights, whether bright field or dark field, the polished sphere will show a ring of light.

On-axis diffuse illumination produces an unique reflection off a polished sphere.
BENCHMARKING ILLUMINATION UNIFORMITY

Using the same setup as used for benchmarking illumination intensity with a camera, capture an image. It is very important that the background material be as uniform as possible with no texture resolvable by the camera. Also, many vision systems and even some cameras provide a function often called “Flat Field Correction” that compensates for non-uniformity across the image. If this feature is available and used in the vision system, it must be disabled for this benchmark. However, it would be interesting and useful to also perform this benchmark with Flat Field Correction enabled if it is available and used in the application.

Figure 21 shows a gray-scale image created with off-axis point illumination to create a noticeable intensity gradient. The image uses 8 bit pixels for a possible 256 levels of gray.

Some statistics for this image that should be recorded for your image:

- Minimum gray value = 52
- Maximum gray value = 187
- Average gray value = 143

The acquired image must be prepared as follows:

1) If using a color image, convert the color image to gray-scale. If color consistency is an issue, you can perform this procedure separately for the red, green and blue channels.
2) Low-pass filter the image to eliminate as much of the image noise as...
possible. Since you are looking for gradual changes in light intensity, the low-pass filtering can be aggressive.

3) Generate a pseudocolor image where each specific range of gray levels (e.g., 255-251, 250-246, 245-241, etc.) is replaced by a specific contrasting color. If the vision system cannot create a pseudocolor image, the offline processing by a program such as PhotoShop can be used.

If the facilities to generate a pseudocolor image are not readily available or will not be available to a technician in the field, an image showing isophot lines can be created as follows:

1) Low-pass filter the image.
2) Decimate the number of gray values in the image (e.g., reduce the number of gray levels from 256 to 128 or 64). Even after filtering, there is so much variation within the range of 1 pixel that the result will be of little value.
3) Create a copy of the image that is filtered and decimated.
4) Erode (or dilate) the image copy. A simple erosion (or dilation) using a 3x3 structuring element is adequate.
5) Take the absolute difference between the two images. This result will be an almost pure black image.
6) Threshold the difference image with a threshold of 1. The result will show isophot lines (contours of uniform intensity). The number of gray levels between each isophot contour is determined by the decimation done above.

Figure 23 shows the processed result from the image in Figure 21. The contour lines are 4 gray levels apart.

If you understand machine vision technology, you can appreciate that the non-uniformity that appears in an image is probably due mostly to the non-uniformity of illumination, but it is also affected by lens effects such as the cosine\(^4\) fall-off, vignetting from the lens, and by the photo response non-uniformity (PRNU) of the image sensor as well as other optical effects.
Benchmarking color is essential for machine vision systems that image color. For monochrome machine vision systems, benchmarking color may be useful for characterizing the illumination.

If you have access to and know how to use a spectrophotometer or spectroradiometer, then these instruments can give excellent quantification of the illumination color. For most machine vision practitioners, these instruments are unavailable. The instruments characterize only the illumination and do not take into account the lens or camera’s image sensor.

For monochrome vision systems, illumination can be broadband (e.g., white) or narrow band (e.g., red LED). However, white light sources are available in different color temperatures, and even LEDs of nominally the same color can vary in their dominate wavelength. The challenge for illumination is to insure, though benchmarking, that the same “white” light or the same “red” wavelength is used. Many monochrome vision systems are unaffected by some change in the illumination spectrum, and have no reason to have the illumination color benchmarked.

For a color vision system, acquire an image of a commercial color chart. From the image of the chart, note the color coordinates of each of the relevant colors (e.g., R value, G value, and B value). It is best to use the color system that is most appropriate for your vision application. So you may choose the RGB, CYMK, L*a*b*, or some other system for recording values.

For monochrome imaging applications there is still a practical way to benchmark illumination color when necessary. Position a color target, such as the Greytag/Macbeth ColorChecker chart (see Figure 24 above) in the field-of-view in a position that can readily be reproduced. Take an image of the chart. Record the gray levels of each of the colored squares. While this doesn’t identify any specific color or light wavelength distribution, it does give a reasonable benchmark metric that will identify an illumination color change.
Distortion is caused by changes in magnification. These changes can be due to the characteristics of the lens that causes magnification to change from the center of the image outward (i.e., pincushion and barrel distortion). It can also be caused by the principal planes of the lens, the image plane (image sensor), and the object plane (field-of-view) not being parallel giving rise to perspective distortion.

Distortion is normally characterized by acquiring an image of a test pattern, either a dot pattern as shown in Figure 25 or a checkerboard pattern. The positions of the centers of the dots (or the corners of the squares in the checkerboard pattern) are measured across the image. It is much easier to measure distortion if the vision system provides these measurements, but while a majority of machine vision software packages offer correction for distortion, most do not give the actual distortion measurements.

Distortion is characterized by the ratio of the difference in imaged and true spacing from the image center to a dot at the corner of an image (in pixels) divided by the true spacing from the image center to where the corresponding dot should be (in pixels). That is:

\[
\frac{\text{Distortion (in \%)} = 100 \times \frac{\text{Imaged Distance} - \text{True Distance}}{\text{True Distance}}}{\text{Note that the acquired and processed image for benchmarking must not be corrected for distortion by the machine vision software. Many vision systems make this correction, and, if used, it must be disabled for this benchmark. However, after measuring the distortion and saving the uncorrected image for reference, it is interesting and useful to acquire another image that is corrected for distortion by the software, measure its distortion, and evaluate the effectiveness of the distortion correction.}}
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Benchmarking Image Noise

Image noise is caused by a number of phenomena including electrical shot noise and image-to-image illumination variation.

Place a target in the field-of-view. While this target can be anything, a uniform neutral gray that gives a fairly bright image that is not in saturation anywhere in the image works best. Take a pair of images. Subtract the two images. Calculate the RMS (root-mean-square) of the pixel values in the resulting image; this is the image noise. The signal-to-noise ratio is the average brightness of the two images divided by the RMS noise.
It is not necessary to benchmark illumination polarization unless you are using a light source that is polarized such as a laser or you are using a polarizer-analyzer with a polarizer over the light source to eliminate glare and glints.

For those situations, use a target designed to identify polarization such as the one from Robin Meyers Imaging shown in Figure 27.

To check polarization, you will need a linear polarizer that you can rotate in front of the camera lens. This may be the analyzer already in use or a separate polarizer if an analyzer is not used (don’t use a polarizer together with the analyzer as this will yield misleading results).

You will need to know the direction of polarization of the polarizer you are using for benchmarking. Often this direction is not marked. To find the direction of polarization, take advantage of Fresnel reflection which gives partially (or in a special case, wholly) polarized reflection. Place a shiny object flat on a table. Reflect a light off the object at around 60 degrees down from the vertical. View the glare off the object through the polarizer. Rotate the polarizer until the glare is minimized. At this point, the polarizer’s direction of polarization is vertical.

Next place your polarizer in front of the camera’s lens with the analyzer, if any, removed from the lens and the polarization test card in the field-of-view. With the machine vision illumination ON, rotate the polarization until the reflection off the metalized bars is as dark as possible. Note the direction
of polarization for the polarizer you have placed over the lens. This direction is 90 degrees from the direction at which the illumination source is polarized.
SUMMARY

If the benchmarks described in this paper are performed on a vision system that is working well or on a laboratory setup that has proven the imaging satisfactory, then if that vision system ever needs maintenance or if there is ever a requirement to reproduce the vision system’s imaging, the maintenance technician or vision engineer can perform their task with assurance that they have restored or built the vision system to a performance that is equivalent to the earlier qualified vision system.