Chapter 2

Colour image acquisition

As we aim to work on machine vision problems, where colour is one of the main cues to take in regard, the acquisition system is the first issue to deal with. It is not the same to construct a system to get geometrical or structural measures than defining the best way to acquire a surface under spatially–homogeneous conditions. Another feature that the system has to obey is the ability to measure small colour differences. We will analyse the relevant parameters of the CCD cameras and their involved problems and how to solve them. We also focus on the construction of a lighting architecture for a surface inspection system. Taking into account these requirements let us examine the different alternatives, and the proceedings that should be done.

2.1 Dark current

In this chapter we are assuming that the image acquisition is done by means of a CCD device. It could be done using other type of sensors, such as CMOS devices but, up the moment, CCD's are the most suitable for high performance and *low cost* imagery. In such devices the pixel information comes from a photo-sensor and the circuitry involved in transforming emitted light to a digital or analog quantity. In an ideal case [43], given a point in the light emitted $L(x, y)$ the final result $Z(x, y)$ should be

$$Z(x, y) = tL(x, y)$$

where t includes the exposure time and the factors involved in the manipulation of the signal. However it is not the case. Many problems affect the acquisition process; some of them are noise, black current and sensitivity irregularities. Combining these effects the final representation is given by

$$Z(x, y) = D_t(x, y) + tF(x, y)L(x, y) + N(x, y)$$

where $D_t(x, y)$ (*dark field*) is the signal from the *dark current signal* (also called *thermic noise*) [55]. It is induced by thermal excitation of the CCD components and

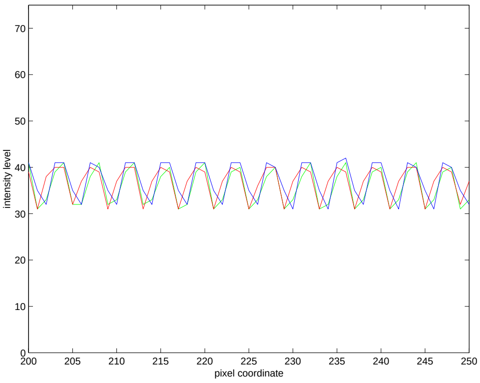


Figure 2.1: Example of a dark field for a TVI line scan camera. When acquiring an image without dark current signal correction, the colour information has 35 intensity levels above what it should be.

may vary with position in the array of photo-sensors, and exposure time. $F(x,y)$ is the function that captures the relative sensitivity of the device in each position of the CCD array in relation to its ideal behaviour. $F(x,y)$ is known as the *flat field*. $N(x,y)$ is the intrinsic noise of the system. Both $D_t(x,y)$ and $F(x,y)$ can be avoided but not $N(x,y)$. Usually $N(x,y)$ is defined as a constant amount in *db* all over the sensor and related to the input signal (*signal–to–noise–ratio*), and it should be provided by the manufacturer. Our first choice is the camera with the less noise level. Later in this chapter we will describe how to solve the dark current signal problem. Although the flat field defines the CCD sensitivity it could be analysed with other effects introduced by the optics and lighting conditions as a whole. This will be studied in the next chapter.

As $D_t(x,y)$ is an additive signal and supposing that the $N(x,y)$ signal is small enough, it could be easily subtracted from $Z(x,y)$. Getting $D_t(x,y)$ is as simple as setting $L(x,y) = 0$, that is covering the entrance of the light, so that $Z(x,y)$ only respond to the dark current signal. However, and in order to minimise the effect of the intrinsic noise, we need to average several dark fields. Another parameter that is significant in the resulting dark field is the effect of the exposure time. The coefficient t represents the fact that the dark current depends on the amount of time the CCD is active. This means that a set of dark currents corrections should be recorded for each different exposure time our system will work. Fortunately, most of the industrial vision problems work at a fixed cadence, and we only need one such a measure.

The last point that we should be aware of is the effect of the device temperature. Dark current increases when the temperature increases. To solve this problem the sensor is cooled using liquid nitrogen (in the most expensive case) or using forced–air cooling which is the cheapest solution, among other possibilities [15]. In industrial application the forced–air cooling is the most used solution. This solution stabilises the temperature after some working time. It should be considered, and take the correction dark field information after one hour and a half the camera comes into operation, as an average. Figure 2.1 shows an example of the dark field calculated from a small section of a TVI line scan camera line response. It should be noticed there is a difference of 35 intensity levels on average between the real acquired image and the corrected one. That means colours become overemphasised in some cases. Moreover, this particular case seems to include problems with the synchronisation between the camera and the frame grabber, although the manufacturers state that it is correct.

2.2 Camera architecture

This section tries to answer to the question of which is the best camera architecture to acquire colour flat surfaces, obtaining the best colour fidelity. The two main architectures used in industrial vision are the matrix array cameras and the linear array cameras. Whenever it is possible it is much better to use a matrix camera than a linear one. Some of the reasons for this choice are:

- There is no need of camera synchronisation with the conveyor–belt. Even in the case when the conveyor–belt can not stop, we can use non–interlaced matrix cameras with high shutter speed to remove the motion blurring effect. In the case of line scan cameras the exposure time, the horizontal synchronisation and the vertical sync signal have to be adjusted to the cadence of the production line. The last one of these parameters is the most sensitive to produce a good result.

- It is easier to focus the scene. As what we see in the monitor is what we get it is quite obvious to focus the scene without using any artifice. In linear array cameras what we see is just a line of the scene and it is difficult to visually focus the image from a scene that could be complex. Some simple and a priori known patterns should be used for this purpose.

- There is no need to perfectly align the acquisition system with the transporter system. Whereas when using a matrix camera we get an image of the scene in a flash (stoping the conveyor or any other means), it is not possible with a line scan camera.

When choosing a colour matrix camera it is important to use a 3 CCD instead of a 1 CCD camera. The colour sensitivity is much better in the first case because when using a 1 CCD camera, the responses on the red, green and blue channels are mixed in the same CCD, obtaining less spatial colour resolution.

However, there are some cases where matrix cameras are not suitable to the inspection problem. One set of them is that involved in this work: industrial vision problems where the solution needs a very accurate degree of colour representation on the acquired image. The problem of obtaining a good image is not from the camera itself but from the lighting system. Now, we are going to examine which are the options and the pros and cons for both cases.

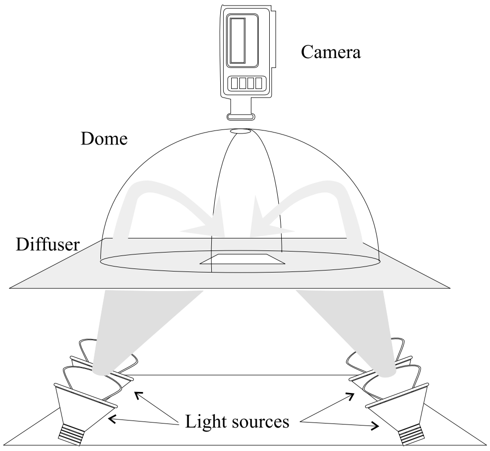
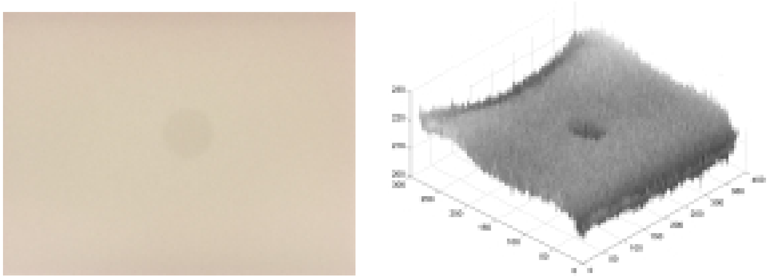


Figure 2.2: Lighting architecture for matrix camera acquisition. The light is diffused using a reflective dome and a diffuser material to avoid predominant light directions from bulbs.

2.2.1 Lighting for a matrix camera

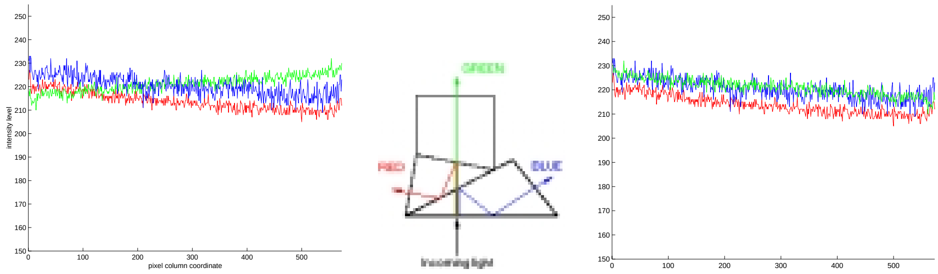
In this section we will explain why the matrix camera performs badly in colour accuracy. Although there have been interesting developments on how to place lights to get uniform frontal illumination [45], we have not succeeded in getting good homogeneity properties. Therefore, we decided to go to a more directed architecture. The lighting architecture we have used is shown in the the diagram in figure 2.2. The light source comes from below the sample a hits a white dome. The semi–spherical shape of the dome makes the light to reach the sample from all possible directions and angles. This is what makes the illumination to be homogeneous. In the theoretical case it should be a flat back–light surface source but if the dimensions of the sample are greater than a few centimetres there is not such a device. One of the solutions is to diffuse the light sources before entering the dome. In the experiment four 250 watts bulbs where placed at the corners. In this way there should not be predominant directions of light. The dome is opaque to avoid light entering downward. The camera is placed at the top of the dome using a hole as small as possible.

To work with applications that request a very sensitive ability to deal with colour differences, the main point is to get the surface illuminated as much homogeneously as possible. If a constant colour surface is acquired and there are high differences among pixels all over the image, colour processes will not be reliable. We tested the configuration on figure 2.2 to its spatial light homogeneity. Figure 2.3(a) is a 3D display of the intensity level of the red channel of a constant very light brown tile. It should be noticed that there are significative differences between the corners of the acquired image. The differences on the corners of the image are ranged from 4% to 6% of the dynamic range of the camera used in this experiment. Another effect of the dome lighting configuration is that it appears a *hole* in the centre of the image



(a) (b)

Figure 2.3: Lighting non-uniformity for matrix camera acquisition. (a) a sample acquired using schema 2.2 (b) is a 3D representation of the red channel of a constant colour surface.



(a) (b) (c)

Figure 2.4: Lighting non-uniformity for matrix camera acquisition. (a) is the profile of one of the columns of a white surface. All channels should maintain its ratios between them on the whole image. (b) is a diagram of the set of prism to guide the light to the respective CCD of a 3 CCD colour camera. (c) an curious result where the profile run parallel when plotting upside down the green response.

that corresponds to the hole in the highest point of the dome where the camera lens is placed.

Apart from the lighting conditions, other problems are derived from the use of a matrix camera. When acquiring a constant colour surface it is expected that the relationship between channels remains unchanged across the image. There might be changes in the intensity level but, even in this case what is red (or any other colour) should be seen red in any place of the image. We tested two cameras (Sony XC–003P and an equivalent JAI M–90) and both of them behave wrongly. Figure 2.4(a) plots the red, green an blue profile for a certain column of an image of a white surface. While red and blue channels go by parallel, the green channel crosses both of them. The top of the image looks like more reddish than the bottom that looks like greenish. We tested the light changing the position of the bulbs and the behaviour remained the same. The lens was also tested having no change on the profiles. Although it is

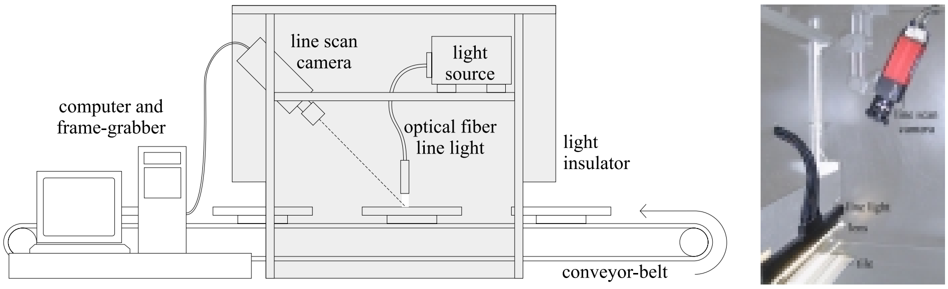


Figure 2.5: Lighting architecture for line scan camera acquisition.

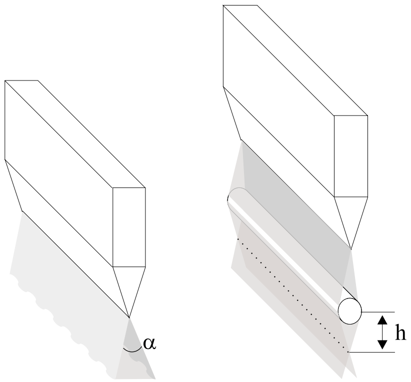
not documented it seems that the reason could be a combination of the prisms used to direct the light to the CCDs and the CCD themselves (figure 2.4(b). A very small de–correlation between the prism and the corresponding CCD changes the behaviour dramatically. But, all in all, what it is more astonishing is the fact than when plotting the vertical profiles of the red and blue channels in the correct way, but the green upside down all the profiles run parallel, as shown in figure 2.4(c). It seems that the green prism has been calibrated in the inverse way that it had should be done. No camera manufacturer has reported such problem. However, this is a point that can not be confirmed and what we can do is to correct this defect or to avoid 3CDD colour cameras presenting this problem.

2.2.2 Lighting for a line scan camera

All the homogeneity problems derived from the use of matrix array cameras could be eluded changing the camera architecture to a linear array one. The basics of the camera are the same except that what you acquire in each step is only one line. This makes a lot of differences when designing the acquisition system. The first problem is that the signal from the camera is not as standard as a matrix camera. It involves more complex and more expensive frame grabbers. Supposing that it is a minor problem let us concentrate on the architecture of the system and the methods to make it work. Although most of them can be easily deduced, it is worthwhile to comment some of them here.

This new architecture will always need a conveyor–belt or any similar mechanism to make the inspection scene run under the camera, an example of a typical design is presented in figure 2.5. Therefore, it is one of the solutions for those applications where the target can not be stopped or it is a non–end production line. But what it is of interest to a surface inspection system is the fact that only one line is acquired at each frame. This is a great advantage when designing a homogeneous lighting system. Instead of worrying about getting a rectangular homogenous–lighted area it is only necessary to achieve a thin homogeneous light strip, which is simpler. There are several manners to do this:

- The first option we have considered is the use of a line optic fibre connected to



(a) (b)

Figure 2.6: Lighting architecture for line scan camera acquisition.

a light source, as can be seen in figure 2.5. The type of light source will be an important choice. We have considered two options:

- A tungsten halogen lamp is the most common choice, but its spectral colour distribution has taken different problems. This lamps has a colour temperature of 3200°K, that is a very reddish light. Considering that digital cameras without any IR filter tend to have much more sensitivity on the red sensor than on the other two, we needed to use a set of blue filters that makes to loose a great amount of light, and you need to increase the number of light sources in four times.
- A second option was the use of a metal halide lamp. This type of lamp is used by professional photographers when they want to simulate indoor sun light. It has a colour temperature around 6000°K, that is a bluish light that does not increase red sensitivity of sensors and there is no need to add more light sources. Furthermore, its life is 5 times the life of tungsten halogen lamps.

Following with this architecture, when using an optic fiber line light the light beam is not parallel but spreads as a cone, like the diagram of figure 2.6(a). In this way a great amount of light is wasted, and considering that the aperture of the optic should be as much closed as possible for increasing the depth of view this is an important factor in the final design.

Moreover, line scan cameras work at a very high frame rate which translates to a very short exposure time interval and so more light is needed. To solve this problem we can use a lens to focus the light beam wherever we like as in the figure 2.6(b). This schema was also used in [83]. One more point to take into account in this architecture is the distance of the sample to inspect to the lens. Ideally it should be at a distance h from the lens to maximise the amount of light available, where h is the focus distance of the selected lens. Nonetheless,

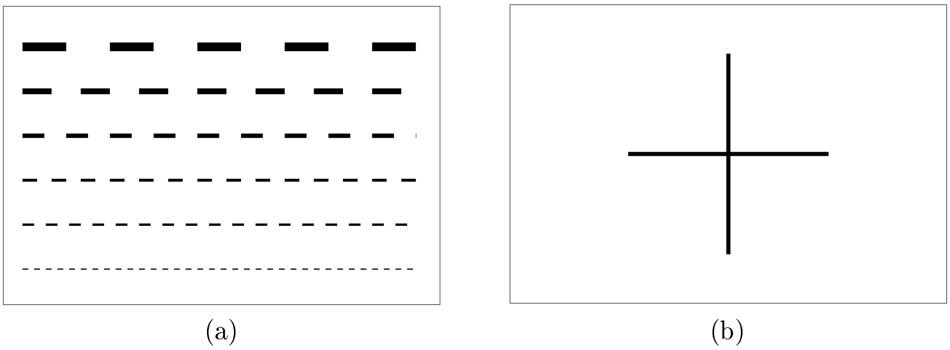

(a) (b)

Figure 2.7: The patterns used to calibrate a line scan camera. (a) pattern used to align the array sensor and the transporter device, and to focus the optic system. (b) simple pattern to guide the synchronisation of camera an conveyor–belt.

this is not the correct answer. The line acquired with the camera is very narrow, and if the light beam is very thin then it would be very difficult to maintain a constant illumination all over the line. Therefore, the sample should be placed at a distance h' smaller than h. As smaller the h' the easier will be getting a homogenous illuminated surface and the darker it will be. The best h' will depend on each single application.

- Another option is to use white light emitting diodes arrays. The LED array is a very long life system but is must be build ad hoc for each problem. In such a system each diode should be controlled individually to equilibrate the amount of light on the line. We do not know of any commercial system with these characteristics.
- One more flexible solution is the use of fluorescent lamps that have the inconvenient of its low lighting power. This is solved by using special lamps that do not coat a small strip of the glass. Thus, the light in this strip is more intense and can be directed to the sample. This solution is the one that is currently working in laboratory conditions.

In the preceding section it has been noted that some artifices have to be used to align, focus and synchronise the line scan camera. The methods most widely used and that we have applied to our inspection line are explained below.

Aligning and focusing a line scan camera

The first step once the camera is set up for acquiring is to align the sensor array with the conveyor–belt. It is an operation that on most cases must be done in static mode. While in the case of matrix array cameras what we will acquire is exactly the scene under inspection and it can be easily tested for focusing, in the case of line scan cameras we do not have this intuitive feedback. It is difficult to understand what you are seeing when only one line of the scene is visible. To fix this obstacle we use a very simple line pattern (figure 2.7(a)). It is very useful not to use a fixed pattern but a set of patterns from coarse to fine. In a first moment the coarsest one is used for an initial configuration, then the pattern is changed for a finer one until the desired precision is achieved.

The second step involves setting up the optics focus. In fact it could be done at the same time that aligning is done. Some manufactures suggest using an oscilloscope to monitor the output signal from the camera. This approach needs some skills on electrical engineering and is not very intuitive because, apart from the sample acquired signal, there are electrical signals as line–transfer, back porch, end porch, etcetera that make difficult its interpretation. One simple way to do it is to plot the profile of the response of one single line from the image acquired. The steeper the changes are in the transitions between white and black the more focused image we get. This step can be automatised by any auto–focus process as for example, maximising the energy from a contour detector.

Synchronising a line scan camera

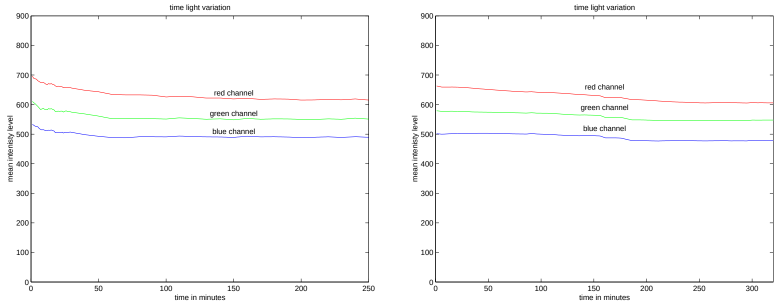
The last problem is to make the pictures have a 1:1 spatial ratio, *i.e*: they should maintain the proportion of the real scene. The best way is to use an encoder to synchronise the speed of the conveyor–belt with the line rate of the camera. Sometimes it is not possible, difficult or unnecessary because the speed is always maintained constant. In these cases an initial set up is essential. It could be fixed using a known simple geometric pattern as a cross, like in figure 2.6(b). The extreme points of the cross are detected by means of morphological operators (for example: *hit or miss* operator) or blob analysis, and the ratio between the vertical and the horizontal line length evidence whether the line rate should be augmented (or conveyor–belt speed down) or viceversa. This is an iterative process until the following ratio is 1.

$$R = \frac{\textit{horizontal line length}}{\textit{vertical line length}},$$

$$\text{synchronisation action} = \begin{cases} \text{increase line rate} & \text{if} \quad R > 1 \\ \text{decrease line rate} & \text{if} \quad R < 1 \\ \text{no action} & \text{if} \quad R = 0 \end{cases}$$

2.3 Temporal stability

In 2.1 we have commented the effect of the temperature on the dark field current intensity, hence whichever it is the camera architecture we have to test the temporal stability of the whole system, camera, optics and lighting. What we have done is to take images of an homogenous sample every 5 minutes until the system stabilises. We tested two configurations to know which part of the system is more sensitive to the warming up. In the first case (figure 2.8(a)) the camera and the light had been switched on at the same time when they are at ambient temperature. In the second case (figure 2.8(b)) the camera was warmed up for two hours before turning on the light. The tests show that the effect is more intense when the camera is cool, but it is more lengthy when the light that is not warmed up. The camera needs one hour



(a) (b)

Figure 2.8: Stability of the acquired signal. (a) Evolution of the signal when switching on the camera and the light at the same time. (b) evolution of the signal when the light is turned on after two hours the camera has been switched on.

approximately to become thermally stable whereas the light needs up to two hours. In any case the maximum of these times will be the warming up time. Although other cameras and illuminations have been tested, the case shown as an example is on a TVI lines scan camera with halogen tungsten lamp. The times may vary if camera or lighting is changed. In each particular case this test has to be done.

2.4 Discussion

As a conclusion we want to note the importance of the dark current signal calibration in any industrial application with high colour (or gray) detail needs.

On the other hand, we think it is advisable to use a linear camera whenever it is possible because of its ability to deal with uniform lighting and avoiding transversal colour aberrations of some 3CCD matrix cameras.

However, the use of linear cameras involves some extra work to be done. More tricky methods are needed to focus the image, and additional hardware or extra methods have to be designed to synchronise the whole system.

As the last point to mention is the necessity of a pre–warming time to assure the correct operation of the system, especially when most of the calibration processes are done at the launch of the inspection (or whatever task) system.