Chapter 10
Integrating Planning with Active Illumination

The performance of the vision perception of a robot, and thus the quality of knowledge learnt, can be significantly affected by the properties of illumination such as intensity and color. This chapter presents strategies of adaptive illumination control for robot vision to achieve the best scene interpretation. It investigates how to obtain the most comfortable illumination conditions for a vision sensor. In a "comfort" condition the image reflects the natural properties of the concerned object. "Discomfort" may occur if some scene information is lost. Strategies are proposed to optimize the pose and optical parameters of the luminaire and the sensor, with emphasis on controlling the intensity and avoiding glare.

10.1 Introduction

Traditional methods for machine vision to better interpret scenes are usually focused on post- image processing (e.g. smoothing, filtering, masking, zooming, contrast stretching, pseudocoloring, etc.). However, post- image processing does NOT increase the inherent information content, but an originally better image contains more information of object surfaces. This facilitates further vision analysis and saves time-consuming enhancement processing, which is very important in a machine vision system, especially for real-time applications.

The provision of adequate light for various human activities has been a matter of some importance since the emergence of civilization. The basic question that has faced the lighting designer is "how much light do we need to see". The IES has dealt with this central problem since its beginning in 1906. In 1937, and again in 1959, a different approach was taken, based on improved understanding of the basic processes involved in vision, seeing, and performing visual tasks. The resulting work formed the basis of the illuminance recommendations of the CIE and for many years was the foundation of the IES method of prescribing illumination.

Much in the same problem, in the computer vision field, while some of the vision systems mentioned by other researchers previously have explicitly dealt with the planning of lighting parameters, current work in illumination planning is quite restricted. It should be recognized, however, that the problem of planning general lighting for machine vision is extremely difficult. Most of the work has used point sources of light that are incident on convex Lambertian surfaces. These models, while useful, are not analogous to actual lighting conditions seen in current applications. Higher-order lighting/reflecting models that include such phenomena as multiple sources (both point and extended), specularity, and interreflections from concave surfaces need to be found to properly plan lighting parameters.

The light source for a natural scene is its illumination. As with any light, illumination has the properties of intensity and color, which significantly affect the performance of the robot vision perception as well as human perception. This chapter mainly considers the most widely used “robot eye” – the CCD camera.

“As in real estate where the key to successful investments is location, location, location, in machine vision the key to value (equal to success) is lighting! lighting! lighting!” said Nello Zuech, the President of Vision Systems International.

The principal reason for success in machine vision is the elimination of appearance variables and the consistent appearance that appropriate, application-specific lighting yields. Unlike the early days of machine vision when many of the entrepreneurial researchers in pioneering machine vision companies suggested, “We just need an image, our image processing and analysis algorithms will work for your application,” today people acknowledge the importance of lighting and scene consistency.

The light source for a natural scene is its illumination. For many machine-vision applications, lighting now is the most challenging part of system design, and becomes a major factor when it comes to implementing color inspection. The uniformity and the stability of the incoming lighting are usually the common causes of an unsatisfactory and unreliable performance of machine-vision systems. As with any light, illumination has the properties of intensity and color, which significantly affect the performance of robot vision perception as well as human perception.

The selection of light sources and vision sensors constitutes the first problem in vision design. There are many different kinds of sources, including incandescent filament lamps of many kinds, short arc lamps, gaseous and solid-state lasers, fluorescent lamps, high-intensity gaseous discharge lamps, electroluminescent lamps, light emitting diodes, carbon arc lamps, etc. Most CCDs have good red (long wavelength) response, but blue response can be a problem because of absorption in the polysilicon layer that covers the sensitive area. Using back-illuminated sensors may help to avoid this problem. Furthermore, a lot of camera series are ready for industrial use. It is important to select proper parameters, such as focal length, imager size, resolution, angle of view, etc.

Then optical settings and geometrical placements of the light source and the vision sensor become another problem. To solve this, we must firstly analyze what “a perfect image for machine vision” is. A good image means that it contains maximum information about the scene so that the robot can easily understand it. The evaluation criteria of illumination conditions should be given and then the degree of “comfort” to the machine eye may be analyzed.

Effort by Eltoft and de Figueiredo (1995) is one of the earliest important attempts in illumination control, and there is other literature with some relations to this problem (Gudrun 1990, Sato and Sato 1999, Ding et al. 2000). Recently, researchers have become more aware of the subject (Muehlemann 2000, Hartmann et al. 2003, Qu 2003, Martinez-De-Dios and Ollero 2004). Their work discusses many factors of illumination conditions that affect the quality of the image.

Although Chap. 3 has listed some typical works on illumination planning for active vision, this chapter further discusses many factors of illumination conditions that affect the quality of images seen by a robot. However, in our preliminary work, intensity control and glare avoidance are emphasized and fundamental sensing settings and spatial placements are proposed for active illumination setup in practical vision systems.

10.2 From Human Vision to Machine Vision

Currently CCD cameras are still the most commonly used machine eyes because of their many advantages, although CMOS cameras are also widely used nowadays. Apart from the apparent structure and working mechanism, a machine eye works very similar to a human eye with some comparable characteristics like resolution, bandwidth, luminosity, the ability to distinguish, adaptivity, and color vision.

For resolution, the ability of human vision to perceive fine detail is called acuity that is expressed as the angle subtended by the smallest object he can discern. For gray-scale objects, this is typically about 1’ (minute of arc). A typical camera has an acuity of about 4’. To the human eye’s bandwidth, electromagnetic radiation in the wavelength range from 400 to 700 nm is what we know as visible light and has peak responsity at 555 nm. A typical CCD element (with photodiodes or photogates) is sensitive within a wavelength between 300 and 1100 nm and has peak responsity at 800 nm. But it is practically cut off between 400 and 700 nm using filters and is normalized to meet the human sensitivity curve.

A human observer perceives the intensity (energy level) of light as the sensation called brightness. However, the perceived brightness varies depending on the color of the light. This is quantified by a luminosity curve. Usually a video camera is designed to have a spectral response that matches the similar luminosity curve. Humans can detect dozens of levels of intensity within a scene, which is referred to as gray-scale response, and thousands of colors. Present common cameras can detect 2^8=256 different gray levels and 2^{24} true colors.

Concerning adaptivity, it is well known that the human eye adapts to average scene brightness over an extremely wide range, as much as $10^{10} – 1$. Video cameras are designed to deal with a similar brightness range and provide gray-scale reproduction pleasing to the eye. They use a serial of f-numbers to adapt to the brightness and at a certain f-number the dynamic range is only thousands of lux.

10.3 Evaluation of Illumination Conditions

We will now give some quantitative criteria to evaluate the quality of illumination conditions in a specified vision task. These criteria reflect the factors of signal-to-noise ratio (SNR), linearity, contrast, and natural properties of the object.

10.3.1 SNR

SNR is one of the image fidelity criteria that is an important factor in considering illumination control and is measured by determining the amount of random noise on the visual signal in an area of the scene (object). A higher number of SNR produces a picture with enhanced sharpness or other attributes.

The SNR is defined as

$$\mathrm{SNR} = 10\log_{10}\frac{\int_{\Omega} i(x,y)^2\,\mathrm{d}\omega}{\int_{\Omega}[i(x,y)-\hat{i}(x,y)]^2\,\mathrm{d}\omega}\ [\mathrm{dB}] \tag{10.1}$$

where $i(x, y)$ is the input signal (scene information) under certain illumination conditions, $i(x, y)$ is the corresponding noised signal, and Ω is the whole field of view.

However, noise measurement is affected by the use of aperture correction or image enhancement and may also be affected by the presence of shading or nonuniform illumination.

Noise generation in CCD imagers has several sources. The fundamental noise level results from the quantum nature of the incident light – as the light on a pixel reduces, fewer light quanta and, thus, fewer electrons are involved, and the signal gets noisier. However, this is usually not a serious limit. More important is the dark current performance of the CCD; this is a small current that flows in the absence of light input. It depends on temperature and may vary from pixel to pixel. Random fluctuations of the dark current are visible as random noise. Another CCD noise source is reset noise, which originates in the readout circuit on the chip. Furthermore, the input amplifier is also a noise source.

10.3.2 Dynamic Range

A typical CCD sensor has a limited dynamic range of illumination intensity. That is, the image irradiance l must lie in the range:

$$L_{\min} \le l \le L_{\max}. \tag{10.2}$$

For example, a "SONY XC003P - 3 CCD Color Camera" has a minimum sensitivity of 31 lux (at F2.2, GAIN +18dB, 100% level) and a normal sensitivity of 2000 lux (at F5.6). The maximum sensitivity is usually not specified because most cameras can automatically handle highlights using a knee slope and white clipping to compress the contrast.

The contrast compression knee is usually at about 90% of the *reference white* level, over which it will cause nonlinearity and loss of scene information. Once the white clip level is reached, all color will be lost and the highlight will appear white.

10.3.3 Linearity

The above interval [L_{min}, L_{max}] is called the gray scale. Common practice is to shift this interval numerically to the interval [0, L] by looking it up in the quantization table. l=0 is considered black and l=L is considered white in the scale. However, the *memory look-up table* is not always linear because of transfer-characteristic processes of the camera, such as gain control, gamma correction, and highlight compression. Usually it has better linearity between 5% and 85% of total gray levels, which corresponds to 12 and 216 of 8-bit signal levels.

10.3.4 Contrast

Original contrast is important in machine vision tasks because it means obtaining clear object surface information. Although contrast can also be enhanced during post-processing (e.g. histogram equalization) of the acquired images, original contrast must be good enough so that it survives the quantization process. High original contrast may help the robot vision system to achieve a better interpretation of the scene.

Considering two surface points *A* and *B*, the survival probability of contrast (apparent difference between *A* and *B*) is

$$p_s = \min(1, \frac{|l_A - l_B|}{\Delta}), \tag{10.3}$$

where Δ is the length of the quantization step, l_A and l_B are illumination intensities of point *A* and *B*, respectively.

10.3.5 Feature Enhancement

The features of interest in machine vision include the geometrical object shape and optical surface properties, which both are represented through reflective responsity and the color vector. Therefore, another purpose of illumination control for feature enhancement is to: (1) improve the contrast of reflective responsity, (2) reflect the true color of the object surface. To achieve this purpose, we need to select the proper luminaire type and carefully control luminaire pose, radiant intensity, and color temperature.

10.4 Controllable Things

10.4.1 Brightness

The minimum light input is limited due to the dark current performance of the CCD, which depends on temperature and may vary from pixel to pixel. Most present CCDs can be sensitive from 2 to 20 (*lx*) at minimum. On the other hand, a brighter scene may bring higher SNR because it contains a larger signal with the same noise and higher image contrast.The basic nature of image brightness $l(x, y)$ is usually characterized by two components: illumination $i(x, y)$ and reflectance $r(x, y)$:

$$l(x, y) = i(x, y)r(x, y). \tag{10.4}$$

Under the same illumination condition, considering two surface points A and B, it is obvious that larger illumination implies a higher contrast between them because:

$$\text{Contrast} = |l_\text{A} - l_\text{B}| = i(x, y)|\, r_A(x, y) - r_B(x, y)|. \tag{10.5}$$

However, too bright an illumination will result in the camera's white balance clipping function and loss of object surface information (both discontinuities and colors).

10.4.2 Color Temperature and Color Rendering Index

The color in an image is derived from a complex combination of incoming illumination, material interaction, and detection parameters. The *color temperature* describes the appearance of a light source when someone looks at the light itself and the *color rendering* is given to surfaces when it shines on them. Generally, illumination in an ideal vision system should be white, which means it includes a broad spectrum of colors. But in a real environment, the light color depends on the types of light sources and their temperatures. Color temperature is the temperature of a blackbody radiator that produces a matching visual sensation to the illuminant. The color temperature of common white light sources ranges from approximately 2700 to 6500 K. For example, incandescent illumination has a color temperature in the range of 3,000 K and is seen as "reddish". Daylight usually is defined as a color temperature of 6,500 K. The locus of color temperatures shows on the CIE (http://www.cie.co.at) chromaticity diagram as a line beginning at the red end of the spectrum for low color temperatures, and curving out toward the center of the diagram for high temperatures. Video cameras have no natural ability to adapt to the illuminant. They must be told what color in the image to make "white" and then a white balancing procedure must be performed.

Practically, while the light from a lamp appears white to humans, a color CCD-camera produces a red rich image. This color variation is due to the imbalance of the lamp's spectral output, and it is further exaggerated by the wavelength-dependent sensitivity of a standard silicon CCD sensor, which has stronger sensitivity to red photons than to blue photons. In many color applications, the use of a balanced white light source is preferred in combination with an off-the-shelf single-chip color camera, with RGB output and good long-term stability, providing an optimum balance between color quality and cost.

The *color rendering index* expresses how a light source compares with natural light in its ability to make objects appear in their natural colors. It is a measure of the degree to which the colors of surfaces illuminated by a given light source conform to those of the same surfaces under a reference light. Perfect agreement is given a value of 100%. Common lamps have rendering indices ranging from 20% to 90%. For example, incandescent lamps – 90%, fluorescent tubes – 60%–90%, high-pressure mercury lamps – 40%–60%, low-pressure sodium lamps – 20%–40%.

Incandescent lamps or filament tungsten halogen lamps are stable, have a fairly long life time, good color rendering, relatively high efficiency, and are easy to install. Spectral irradiance can also be made more uniform by grinding the surface of a glass bulb. Therefore they are good options for machine vision use. A one-point light source is easy for lighting installations, but the disadvantage is non-uniform spatial distribution of illumination intensity.

10.4.3 Glare

High contrast between a luminaire and its background may produce glare. A machine eye may not be able to adapt to this situation because it exceeds the dynamic range of the cameras. It is a cause of visual discomfort because the machine eye must handle the highlight. The contrast is degraded when the highlight compression knee is reached and all color and contrast will be lost when white clip levels are reached. In this case, the robot may have difficulty to understand the scene.

Two types of glare are distinguished: (1) discomfort glare or direct glare, resulting in physical discomfort; (2) disability glare or indirect glare, resulting in a loss in visual performance. They will be discussed in the next sections.

10.4.4 Uniform Intensity

Lighting with uniform spatial distribution is the most efficient solution for a vision system. If the intensity distribution is non-uniform and the pattern is uncalibrated, it will become an additional source of noise and the SNR is degraded.

If the pattern of light source radiation is previously known (through the illumination calibration technique (CIBSE 1985)), we may obtain scene features using:

$$r(x, y) = l(x, y)/i(x, y), \tag{10.6}$$

where $r(x, y)$ reflects the optical properties (edge discontinuities and colors) of the object.

10.5 Glare Avoidance

To the human eye, glare is a source of discomfort because the high contrast between a luminaire and its background exceeds its adaptive dynamic range. This is an even worse situation for the machine eye because the vision sensor has a smaller adaptive dynamic range. Too much illumination volume will automatically cause highlight compression or white clipping. Furthermore, glare usually causes loss of the object's natural color. Hence, two types of glare, disability glare and discomfort glare, should be avoided as much as possible.

There are at least two reasons for vision system to avoid glares. First, a vision sensor has a limited dynamic range. Too much illumination volume will automatically cause highlight compression or white clipping. Second, glare usually causes loss of an object's natural color.

10.5.1 Disability Glare

Disability glare is usually caused by indirect glare and results in a loss of visual performance. Nayar et al. (1991) find that the image irradiance is a linear combination of three components, diffuse lobe I_d, specular lobe I_{s1}, and specular spike I_{s2} (Fig. 10.1):

$$I = I_d + I_{s1} + I_{s2} = k_d \cos\theta + k_{s1} e^{-\frac{\alpha^2}{2\sigma^2}} + k_{s2}\delta(\theta_c - \theta_i)\delta(\varphi_c - \varphi_i) \tag{10.7}$$

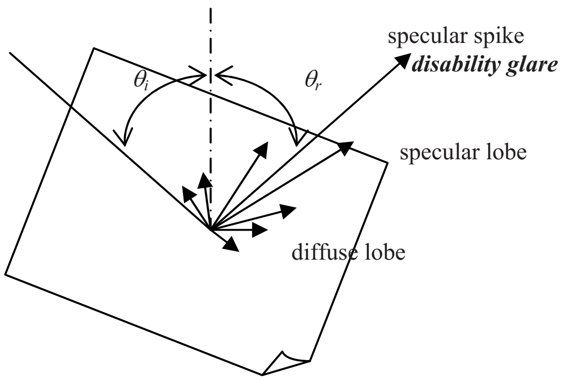


Fig. 10.1. Diffuse reflection and specular reflection

Furthermore, Gudrun et al. (1990) concluded that the light color body reflection (diffuse reflection) is determined by intrinsic characteristics of surface materials and the fact that the light color of a surface reflection (specular lobe + specular spike) has the same color as the illumination. For example, a shiny red ball will have a specular highlight on its surface only at the position where the ball's curved surface meets the normal reflection condition. The highlight has the same color as the illuminant (white) whereas, at all other positions on the ball, the reflection is diffuse and appears red.

The disability glare light causes two problems. One is that the specular reflection contains only source color, which results in the loss of color rending, causing the robot to have possible difficulty in detecting natural features of its scene. The other is that the highlight usually has a large volume of illumination intensity, which results in highlight compression or white clipping.

Practically, we can avoid the disability glare by presenting the target with light mostly from the side, so that the specularly reflected and hence brightest light is reflected off to the side and away from the field of view.

10.5.2 Discomfort Glare

In a lighting system for machine vision, although the main problem may be disability glare, in which the brightness of the luminaires may dazzle and prevent obstructions from being seen, we should also consider discomfort glare in the robot environment. It is usually caused by direct glare (due to the lighting installation) and results in physical discomfort.

There are many criteria to evaluate the glare indices. For example, the IES Technical Report "Evaluation of Discomfort Glare" (CIBSE 1985) sets out the procedure for the evaluation of the glare index in the formula:

$$\text{Glare Index} = 10\log_{10}[0.5\times\text{constant} \sum \frac{\mathrm{B}_{\mathrm{s}}^{1.6}\,\omega^{0.8}}{B_b}\times\frac{1}{p^{1.6}}]. \tag{10.8}$$

Recently, the Commission Internationale de l'Eclairage (CIE) established a new glare rating procedure known as the Unified Glare Rating system (UGR) (Einhorn 1998, Iwata and Tokura 1998) in the form of:

$$\mathrm{UGR} = 8\log_{10}[\frac{0.25}{L_b}\sum\frac{\mathrm{L}_{\mathrm{s}}^{2}\omega}{p^2}], \tag{10.9}$$

where p is the positional index:

$$\begin{aligned} 1/p = {} & [d^2/(0.9d^2+2.3d+4)-0.1] \\ & \times\exp(-0.17s^2/d+0.013s^3/d)+0.09 \\ & +(0.075-0.03/d)/[1+3(s-0.5)^2] \end{aligned}$$

These criteria are initially proposed for the purpose of human visual comfort. According to the comparison of the machine eye and the human eye, the CIE-UGR criterion may be adopted for the design of a lighting system in a robot environment. A glare index below UGR-19 is acceptable and above UGR-25 is uncomfortable.

If the light source itself remains in the field of view and is bright, it can become a source of discomfort glare. Therefore it is best to position the light source behind the camera, either above or to the side. We can also reduce the effects of discomfort glare by increasing the task luminance relative to the luminance of the surroundings. Discomfort glare can also be reduced by: (1) decreasing the luminance of the light source, (2) diminishing the area of the light source, and (3) increasing the background luminance around the source if we can stop down the sensor aperture in this case.

10.6 Intensity Estimation

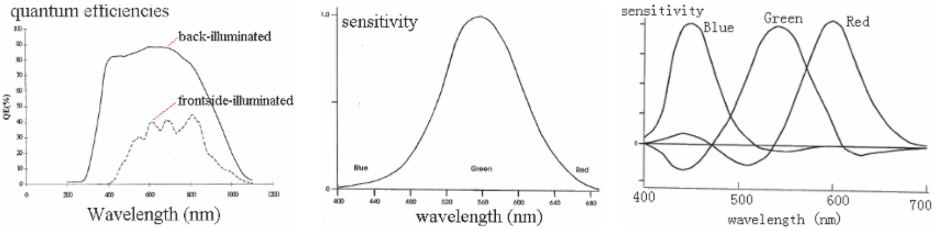
To satisfy the visual comfort of machine eyes, apart from selecting proper types of light sources and cameras, the key controllable parameters of a luminare are radiant intensity and geometrical pose in a practical vision system. The purpose of intensity control is to achieve proper image brightness which is in the range of the sensor, with linear property, and has contrast as high as possible. The purpose of pose control is to avoid possible glare and achieve uniform intensity distribution.

To control the image intensity so that it will concentrate on an optimal point, firstly the sensor sensitivity must be considered, then the image irradiance is estimated from source radiation to image sensing, and finally the optimal control point is decided.

10.6.1 Sensor Sensitivity

The brightness that the camera perceived is the intensity (energy level) of light and varies depending on the light color (wavelength). The sensors usually have most sensitivity at the wavelength of 555 nm with the corresponding efficiency defined as 100%. The distribution is quantified by a curve of brightness sensation versus wavelength, called the luminosity curve. Figure 10.2a illustrates the sensor quantum efficiencies of back-illuminated CCD and front-illuminated CCD (Gilblom 1998). Since a video camera must have a spectral response that matches the human luminosity curve, the curves of sensor sensitivity have been normalized so their areas are equal, illustrated in Fig. 10.2b for 1-CCD and in Fig. 10.2c for 3-CCD. The sensor sensitivity curves are expressed as:

$$\rho_r = \rho_r(\lambda), \rho_g = \rho_g(\lambda), \rho_b = \rho_b(\lambda). \tag{10.10}$$



(**a**) sensor quantum efficiencies (**b**) 1-CCD curve (**c**) 3-CCD curve

Fig. 10.2. Sensor sensitivity (Gilblom 1998)

10.6.2 Estimation of Image Irradiance

To estimate the image irradiance, we need to analyze five procedures, i.e. source radiation, source efficiency, surface irradiance, surface reflection, and sensor perception. First, the total output radiation of a light source at temperature T is proportional to four times the temperature:

$$M_e = \varepsilon\sigma T^4 \tag{10.11}$$

where $\sigma = 5.67051\times10^{-8}\mathrm{Wm}^{-2}\mathrm{K}^{-4}$ and the emissivity $\boldsymbol{\varepsilon} \in [0,\ 1]$ varies with wavelength.

According to *Planck's radiation law*, the spectral distribution of the radiation emitted by a blackbody can be described as a function of wavelength λ,

$$M(\lambda) = \frac{C_1}{\lambda^5}\frac{1}{e^{C_2/\lambda T} - 1} \tag{10.12}$$

where C_1 and C_2 are two radiation constants,

$$C_1 = 2\pi hc^2 = 3.741774\times10^{-16}\ \mathrm{Wm}^2$$
$$C_2 = \frac{hc}{k} = 0.01438769\ \mathrm{mK}.$$

The peak wavelength, $\lambda_{\max}$, in nanometers, is given by

$$\lambda_{\max} = \frac{2.8978\times10^6}{T} = 2.8978\times10^6\left(\frac{\varepsilon\sigma}{i^2R}\right)^{\frac{1}{4}}. \tag{10.13}$$

Equation (10.13) depicts the power output of the light source and the spectral distribution of intensity at different temperatures. As from Fig. 10.3, obviously we can find that with increasing temperature, more energy is emitted and the peak emission shifts toward the shorter wavelengths.

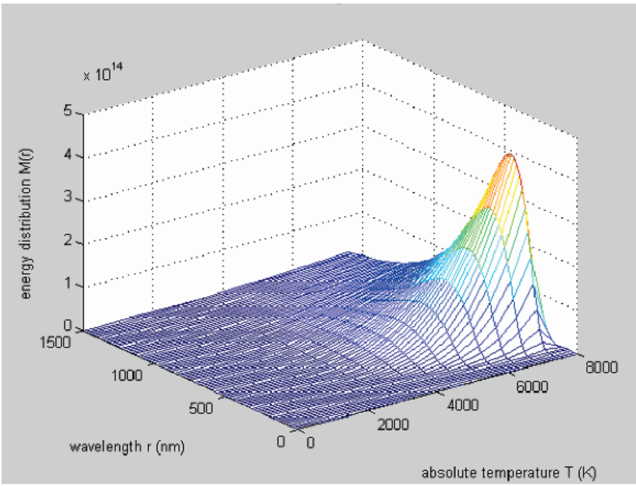


Fig. 10.3. Energy density vs spectral distribution and temperature

Figure 10.4 illustrates the energy distribution of a 100 W incandescent lamp. However, consider that the vision sensor is sensitive only to a portion of the electro-magnetic wave, i.e. 380<λ<750 (nm). Due to the quantum efficiency of the vision sensor, the quantity of light as seen by the camera (illustrated as the grey area in Fig. 10.5.), is

$$W_e = \int_{\lambda_1}^{\lambda_2} M(\lambda)\cdot\rho(\lambda)\mathrm{d}\lambda = \int_{350}^{750} \frac{C_1}{\lambda^5}\frac{1}{e^{C_2/\lambda T}-1}\rho(\lambda)\mathrm{d}\lambda\,, \tag{10.14}$$

where W_e is the efficient light energy.

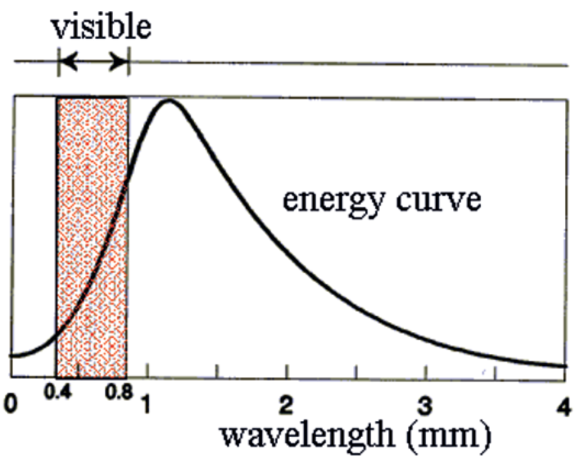


Fig. 10.4. Distribution of source radiation

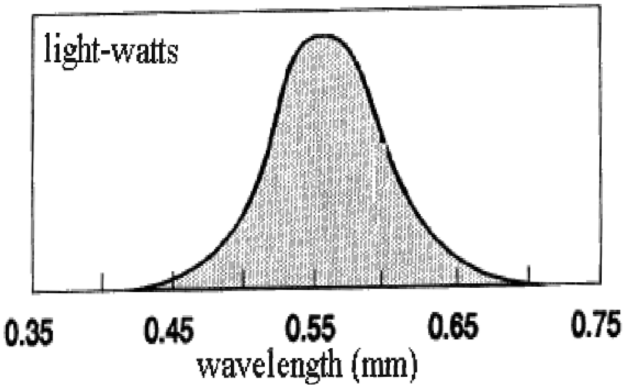


Fig. 10.5. Efficiency of light energy

To control the quantity of source radiation, a dimmer is usually employed to adjust the phase of AC waveforms. Denote the input power rate $\eta(\phi)$ and efficiency $\varepsilon(\phi)$ at phase ϕ controlled by the dimmer, then the visible efficient energy is:

$$W_e = \int_{\lambda_1}^{\lambda_2} M(\lambda)\cdot\rho(\lambda)\cdot\eta(\phi)\cdot\varepsilon(\phi)\mathrm{d}\lambda. \tag{10.15}$$

In the case of a 3-CCD camera, since the color temperature of the light source varies as long as the input power changes, the visible efficient energy becomes:

$$W_{r,g,b} = \int_{\lambda_1}^{\lambda_2} M(\lambda)\cdot\rho_{r,g,b}(\lambda)\cdot\eta(\phi)\cdot\varepsilon_{r,g,b}(\phi)\mathrm{d}\lambda. \tag{10.16}$$

On the other hand, we have

$$L = \int_{380}^{750}\frac{C_1}{\lambda^5}\frac{1}{e^{C_2/\lambda T}-1}\mathrm{d}\lambda \;\underline{\underline{x=\lambda T}}\; T^4\int_{380T}^{750T}\frac{C_1}{x^5}\frac{1}{e^{C_2/x}-1}\mathrm{d}x = C(T)T^4 \tag{10.17}$$

where

$$C(T) = \int_{380T}^{750T}\frac{C_1}{x^5}\frac{1}{e^{C_2/x}-1}\mathrm{d}x = \lim_{\Delta x\to 0}\sum_{380T}^{750T}\frac{C_1}{x^5}\frac{1}{e^{C_2/x}-1}\Delta x \tag{10.18}$$

is defined as a coefficient function.

The following algorithm is developed using numerical computation to solve (10.18), an example curve is illustrated in Fig. 10.6. Finally the luminous flux function (10.17) can be obtained.

"Algorithm for the solution of ***C(T)***"

```
C1=3.74174*(10^(-16));
C2=0.01438769;
e=2.718281828459;
func=zeros(1000,1);

for jt=1:1000;
        T=200+jt*30;
        r1=380.0*T*(10^(-9));
        r2=750.0*T*(10^(-9));
        temp=0.0;
        for i=1:3000;
            r=r1+i*(r2-r1)/3000.0;
            temp=temp+((r2-r1)/3000.0)*C1/((r^5)*((e^(C2/r))-1));
        end;
        func(jt)=temp;
end;
```

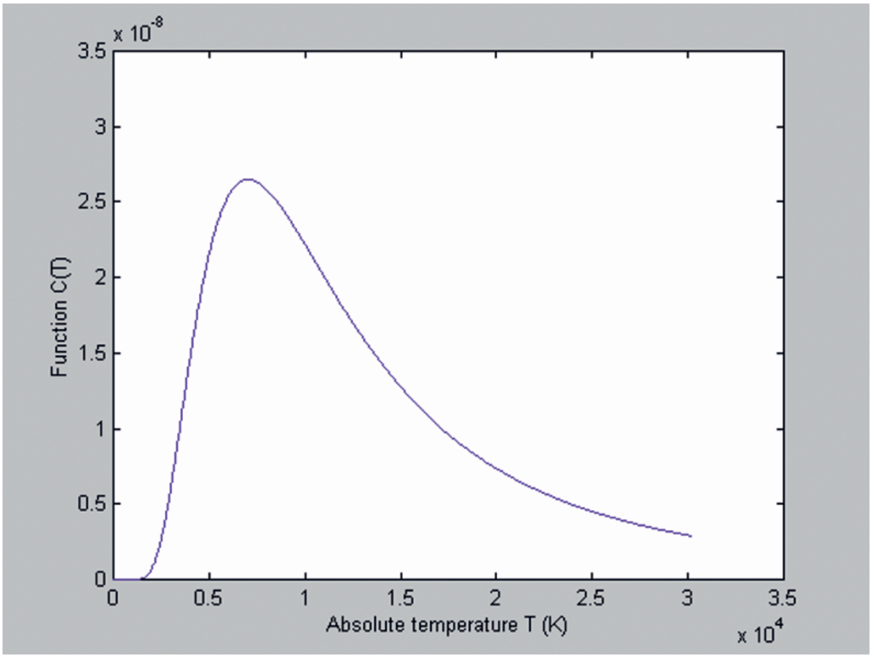


Fig. 10.6. Temperature vs coefficient ***C***(T)

In most cases, the light emitted by a source is usually not uniformly distributed in all directions and the luminous intensity varies according to the position beneath the source. Manufacturers of luminaires usually provide intensity distribution diagrams for their products, which show the relationship between the luminous intensity and the angle to a reference position of 0^o situated vertically below the source. The polar graph is often used for these purposes. It can also be calibrated using the techniques of luminaire photometry developed by Lewin and John (1999). Finally the efficient energy distribution is modeled as:

$$L(\phi,\theta) = W_{r,g,b} \cdot \Gamma(\phi,\theta), \tag{10.19}$$

where the function $0 \le \Gamma(\phi, \theta) < 1$ describes the spatial distribution of source radiation.

Considering a point on the object surface, its irradiance is the integral of the whole angular distribution over a specified solid angle, i.e.

$$L_s = \int_0^{2\pi} \int_0^{\pi/2} L(\phi,\theta)\cos\phi \sin\phi \cdot d_\phi d_\theta \cdot \tag{10.20}$$

The object surface then becomes another source and the image irradiance of the vision sensor can also be computed

$$E = \frac{\pi}{4}(\frac{d}{f})^2 L_s \cos^4 \alpha. \tag{10.21}$$

Since real objects are usually not Lambertians, three parts contribute to the surface reflection, that is I_d (diffuse reflection), I_{s1} (gross specular reflection), and I_{s2} (specular reflection). Then the image irradiance of an object illuminated by a source is represented by a function as in, (Nayar 1991, Laszlo 1999)

$$I = \begin{bmatrix} I_r \\ I_g \\ I_b \end{bmatrix} = k'_d \cos\theta \begin{bmatrix} r_d \\ g_d \\ b_d \end{bmatrix} + k'_{s1} e^{-\frac{\alpha^2}{2\sigma^2}} \begin{bmatrix} r_{s1} \\ g_{s1} \\ b_{s1} \end{bmatrix} + k'_{s2}\, \delta(\theta_c - \theta_i)\delta(\varphi_c - \varphi_i) \begin{bmatrix} r_{s2} \\ g_{s2} \\ b_{s2} \end{bmatrix} \tag{10.22}$$

where $\delta(x)$ is unit pulse function or Dirac delta function.

10.7 Intensity Control

10.7.1 The Setpoint

A camera usually has the requirement of minimum illumination which is typically 2 [lux] with high-gain operation. Theoretically, a camera's sensitivity could be increased as much as desired simply by increasing the amplifier gain and operating the CCDs at a lower output level. Of course, the SNR will degrade when this is done. That is what happens in a camera's "high gain" modes, which trade signal quality for sensitivity. On the other hand, the full-quality mode of a camera operates the CCDs at the light level given in the sensitivity specification. This may be somewhat of a trade-off with highlight performance.

The vision sensor often has best linearity between 15% and 90% of the output level (Fig. 10.7). In fact, the illumination condition below 20% is unacceptable because: (1) low SNR for the existence of noise and dark current, (2) nonlinear quantization at this area, (3) nonlinearity because of gamma correction. An illumination condition above 90% output level is also unacceptable because of contrast compression of the knee slope and loss of color properties. Hence, the optimal setpoint of illumination intensity is at about 80% of the output level because of high SNR, linearity, and contrast.

The illumination intensity can be controlled in two ways: (1) phase-control to adjust the electrical current intensity using a dimmer; (2) pose-control to adjust the distance between object and luminaire using a robot end-effector. Usually it is better to keep the luminaires far away from the object because the illumination will be more uniform in this case and will increase image SNR. It is also better to keep the luminaire in full-on state because it entails a higher color rendering index in this condition and facilitates the obtaining of true surface information.

Machine vision applications have a great need for feedback control. The vision-illumination system can be considered a closed-loop system in which the vision sensor plays a second role as the feedback channel. The pose and dimmer phase are determined by a controller according to the visual feedback, source model, and optimal setpoint. The energy magnitude of source radiation and image irradiance may be estimated using the techniques discussed above.

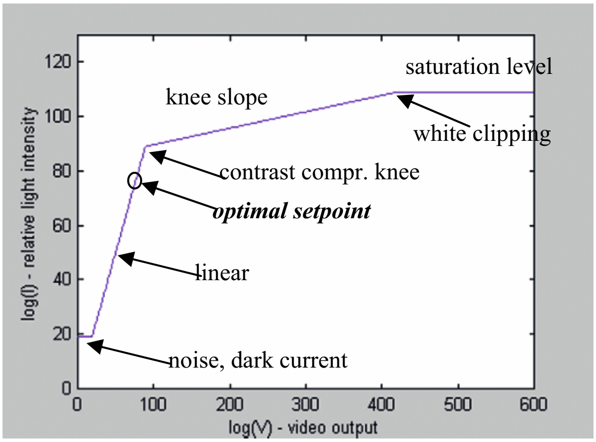


Fig. 10.7. Optimal illumination setpoint

10.7.2 System Design

Figure 10.8 illustrates the overview of a typical system for illumination control, which includes a robot, manipulators of the light source and vision sensors, an image processor, a system controller, and an object in the scene.

Here we focus on the control of the energy magnitude of source radiation, although other parameters may be discussed in future. The block diagram of the illumination control system is illustrated in Fig. 10.9, where the symbols mean:

- x_e: the disturbance of the environment. It results from three reasons: the changing natural light, the dynamic environment, and the moving vision sensor;
- x_o: the sensed image (the output of vision preprocessing).
- x_r: the image irradiance after the displacement of the vision sensor and the illuminants.
- s_{si}: the setpoint of parameters, the output value for setting the vision sensor's parameters and illuminant's parameters. It is a vector $s_{si}=[s_s, s_i]^T$.

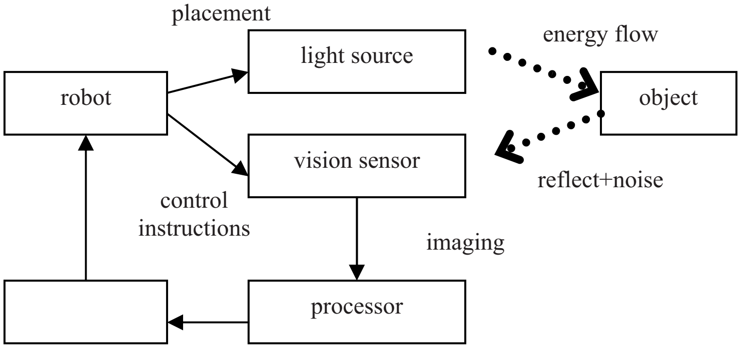


Fig. 10.8. System overview of illumination control

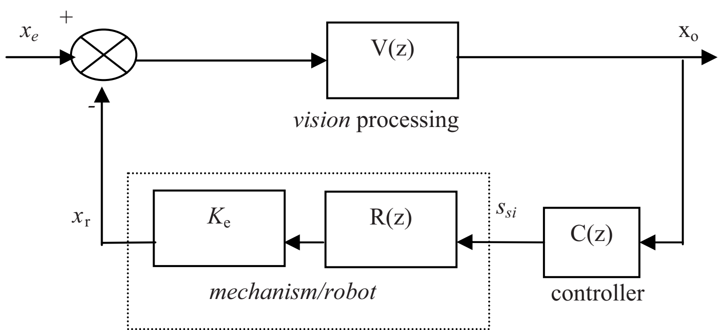


Fig. 10.9. Block diagram of illumination control

- K_e: the gain which relates the image irradiance and the parameters of both vision sensor and illuminant (geometrical pose and optical settings).
- $\boldsymbol{V}(z)$: the vision system. Generally, $\boldsymbol{V}(z)=k_v/z^n$, which means the vision system introduces n unit delays.
- $\boldsymbol{C}(z)$: the controller. It can be a fuzzy-controller or another robust and intelligent controller. It satisfies all above-mentioned constraints and keeps the image from becoming too dark or too bright. The control parameters are based on image irradiance distribution (a statistical value or vector based on the image histogram).

It is an active system with visual feedback. The goal is to keep the object sensed in a good illumination condition to provide good results for further visual processes. In our simulation system, only for testing the principle, a fuzzy-PID controller is used to adjust the parameters of the illuminant. The closed-loop transfer function is:

$$H(z)=\frac{x_o(z)}{x_e(z)}=\frac{V(z)}{1+K_e\cdot C(z)\cdot R(z)\cdot V(z)}. \tag{10.23}$$

where $V(z)=\frac{k_v}{z^n}$ means that the vision system introduces n unit delays for acquiring an image and processing the data. Assume the mechanism (integrator, inverse kinematics, and servo, etc) also produce m unit delays, that is $R(z)=\frac{1}{z^m}$. The transfer function therefore becomes

$$H(z)=\frac{\frac{k_v}{z^n}}{1+K_e\cdot C(z)\cdot\frac{1}{z^m}\cdot\frac{k_v}{z^n}}=\frac{k_v z^m}{z^{m+n}+K_e\cdot k_v\cdot C(z)}. \tag{10.24}$$

10.8 Simulation

A simulation system for illumination control was implemented with MATLAB (Fig. 10.10). The step response, sine response, zero input response, and random input response of the actively illuminated vision system have been observed, while we assume it has 10% environment light noise. Typically, step response happens when the robot stays in a dark room and a light is turned on at a certain time (Fig. 10.11). Sine response happens when the robot walks in an environment with periodically installed lights (Fig. 10.12), for example, a robot moving on a road as in Fig. 10.13. Random input response happens usually in a general natural environment (Fig. 10.14).

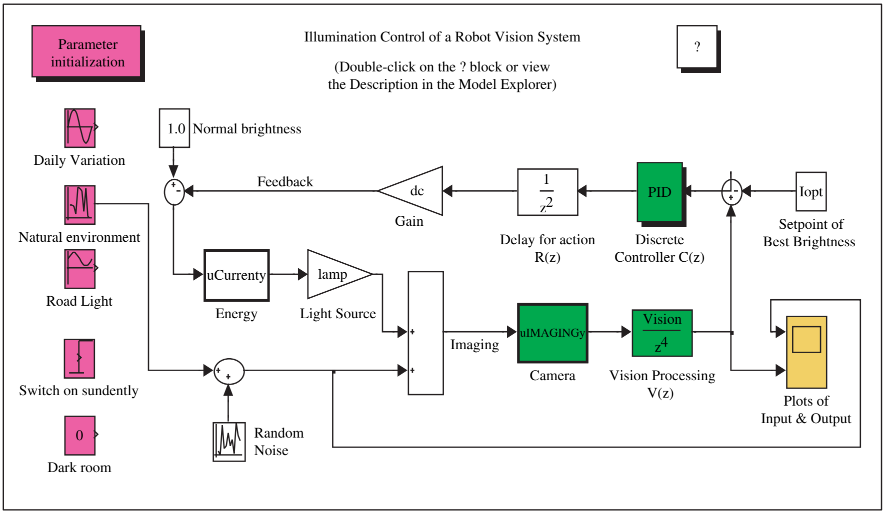


Fig. 10.10. The simulation system for illumination control

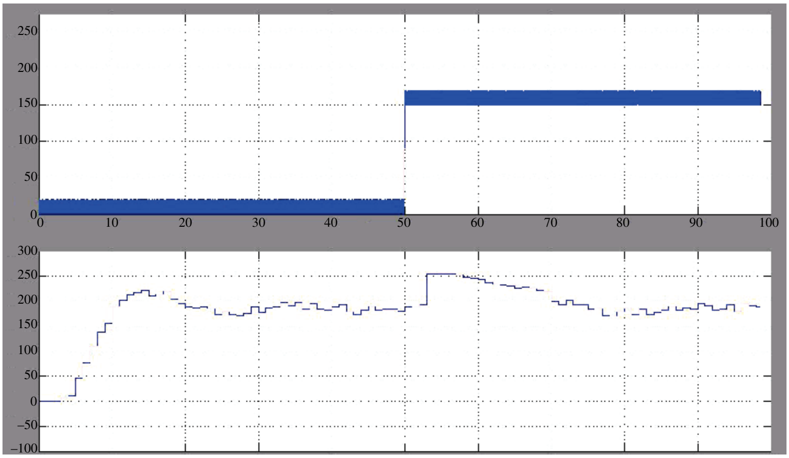


Fig. 10.11. Step response of the actively illuminated vision system, with 10% environment light noise. (It happens when the robot stays in a dark room and a light is turned on at a certain time)

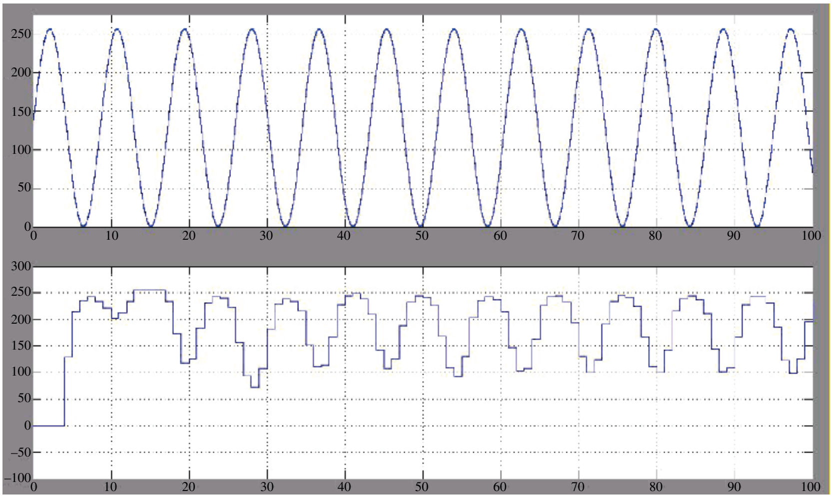


Fig. 10.12. Sine response of the actively illuminated vision system. (It happens when the robot walks in an environment with periodically installed lights, e.g. on a road as in Fig. 10.13)

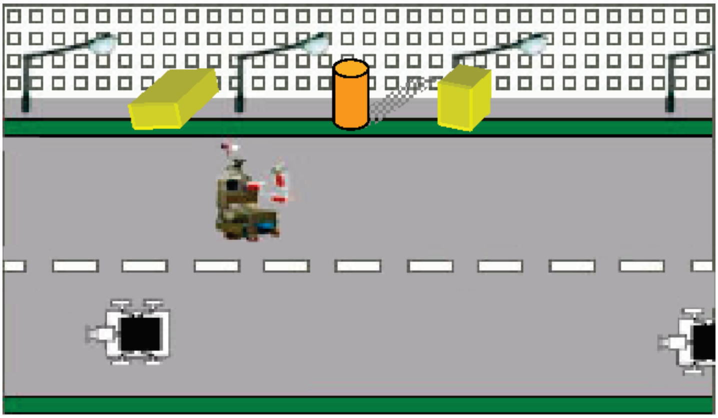


Fig. 10.13. A robot walking in a virtual environment with periodically installed lights

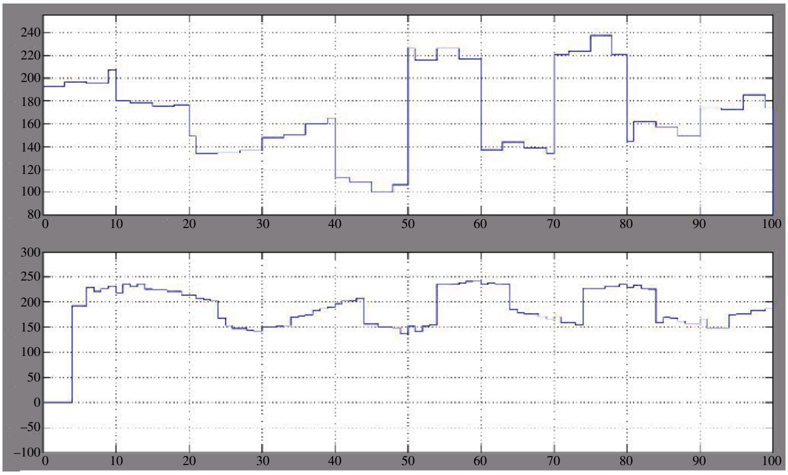


Fig. 10.14. Response of the actively illuminated vision system in a natural random environment, with 10% noise. (In a general environment)

10.9 Implementation

10.9.1 Design for Active Illumination

With thermal light sources, such as electric light, we consider its input power M_0:

$$M_0 = u \cdot i = i^2 R \text{ (watt/s)} \tag{10.25}$$

Since $M_e = \varepsilon\sigma T^4$ (10.11), we have

$$\varepsilon\sigma T^4 = i^2 R \text{ or } T = (\frac{i^2 R}{\varepsilon\sigma})^{\frac{1}{4}} = \alpha\sqrt{i} \tag{10.26}$$

where the coefficient $\alpha = (\frac{R}{\varepsilon\sigma})^{\frac{1}{4}}$ is a constant.

In this way, the radiant intensity and source temperature can be adjusted using a dimmer for phase control. The simplest way is to generate a PWM signal and compare the message signal to a triangular or ramp waveform (Fig. 10.15). The hardware of control module in our laboratory includes a controller board. The controller based on the Atmega16L processor provides several sensor channels, 8.4-24 V input, serial ports (TTL and RS232), PWM mode outputs and on-off mode outputs. As can be seen, we built this module for lighting control. The generated luminance is further calibrated once for generating a control curve.

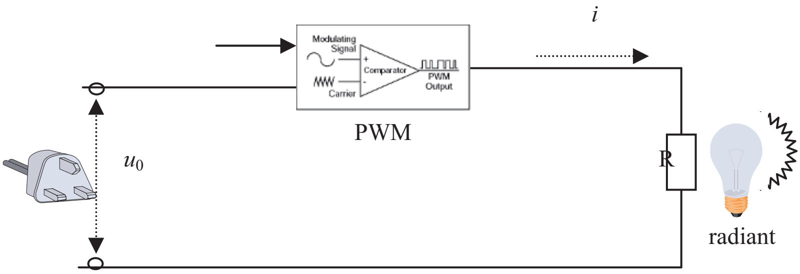


Fig. 10.15. A simple implementation for digital control of radiant intensity and spectral distribution

10.9.2 Experimental Robots

Currently, we are also working on setting up a robot system with active illumination control for testing in real environments (Fig. 10.16) at the University of Hamburg.

Fig. 10.16. The mobile robot setup in our laboratory for dexterous manipulation

The mobile robot has an end-effector with 6DOFs for dexterous manipulation. An eye-in-hand camera is used to observe the scene and the active illumination device contains two light sources which can be controlled by a PWM module (Fig. 10.17). The robot works in many different environments and controls its illumination level automatically. Figure 10.18 illustrates an example of active sensing where the red curve is the brightness of the input image and the blue curve is the output of the lighting level (in percentage). It results in the image sequence being kept in a good range of brightness for scene understanding. A next step of our work is to equip a mobile robot with controllable illumination for active search and recognition tasks, which cannot only adjust the illumination level but also change the lighting direction and avoid glares (Fig. 10.19).

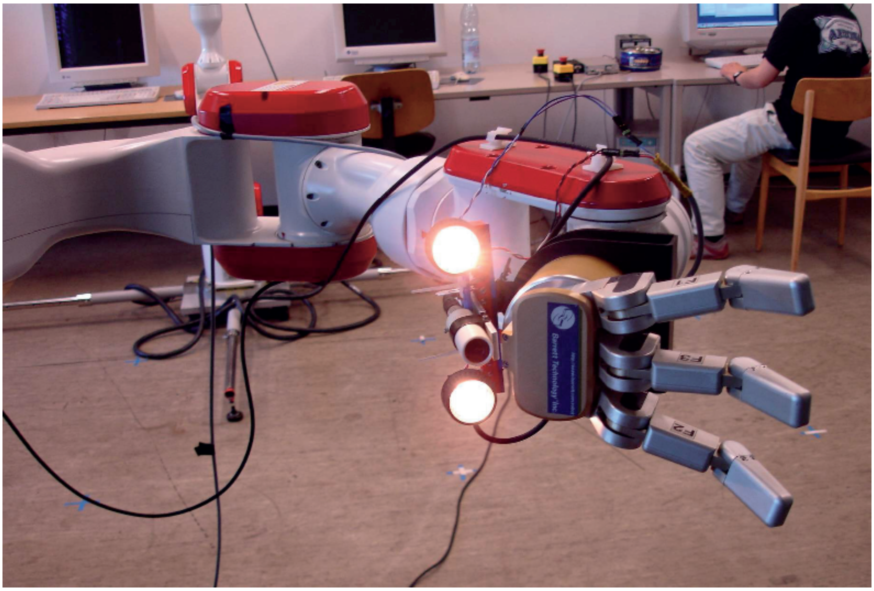


Fig. 10.17. The active illumination device (one eye-in-hand camera and two light sources controlled by a PWM module)

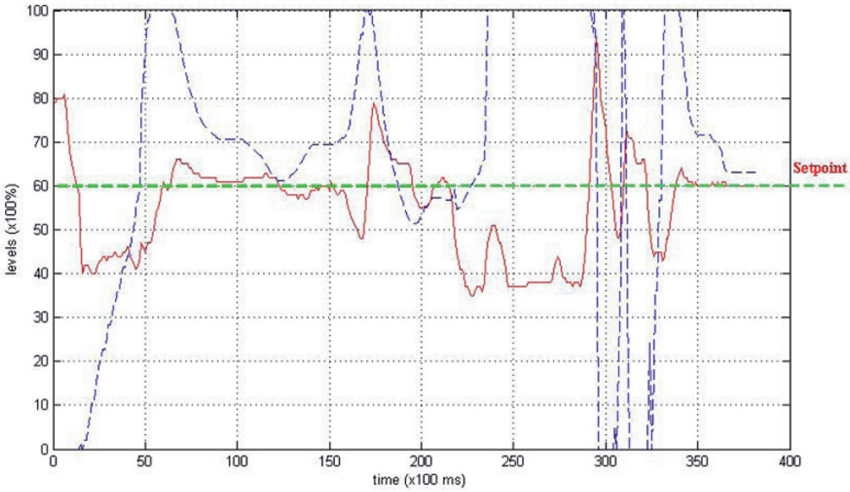


Fig. 10.18. An example of illumination control for active sensing where the solid curve is the brightness of the input image and the dashed curve is the output of the lighting level (in percentage)

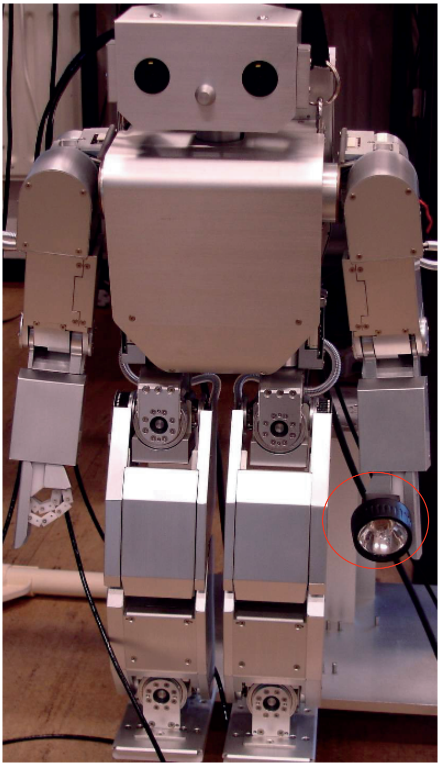


Fig. 10.19. A robot equipped with controllable illumination for autonomous tasks of active search and recognition

10.10 Summary

This chapter presented an idea of active illumination control for robot vision. Strategies are proposed to achieve optimal illumination conditions for vision sensors so that best-quality images can be obtained with high SNR, contrast, color rending, and linearity. The controllable parameters include optical parameters and pose parameters of luminaire and sensor. The characteristics of a robot eye and its "comfort" conditions have been analyzed. The image intensity is theoretically controlled at a good setpoint. Glare avoidance methods are proposed for treating two types of glare, disability glare and discomfort glare. The disability glare can be eliminated by placements of the light source, vision sensor, or targets. The discomfort glare is evaluated using the CIE-UGR criterion and can be diminished by control of the source position, radiant flux, or background luminance.