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Carsten Steger, Markus Ulrich,
Christian Wiedemann

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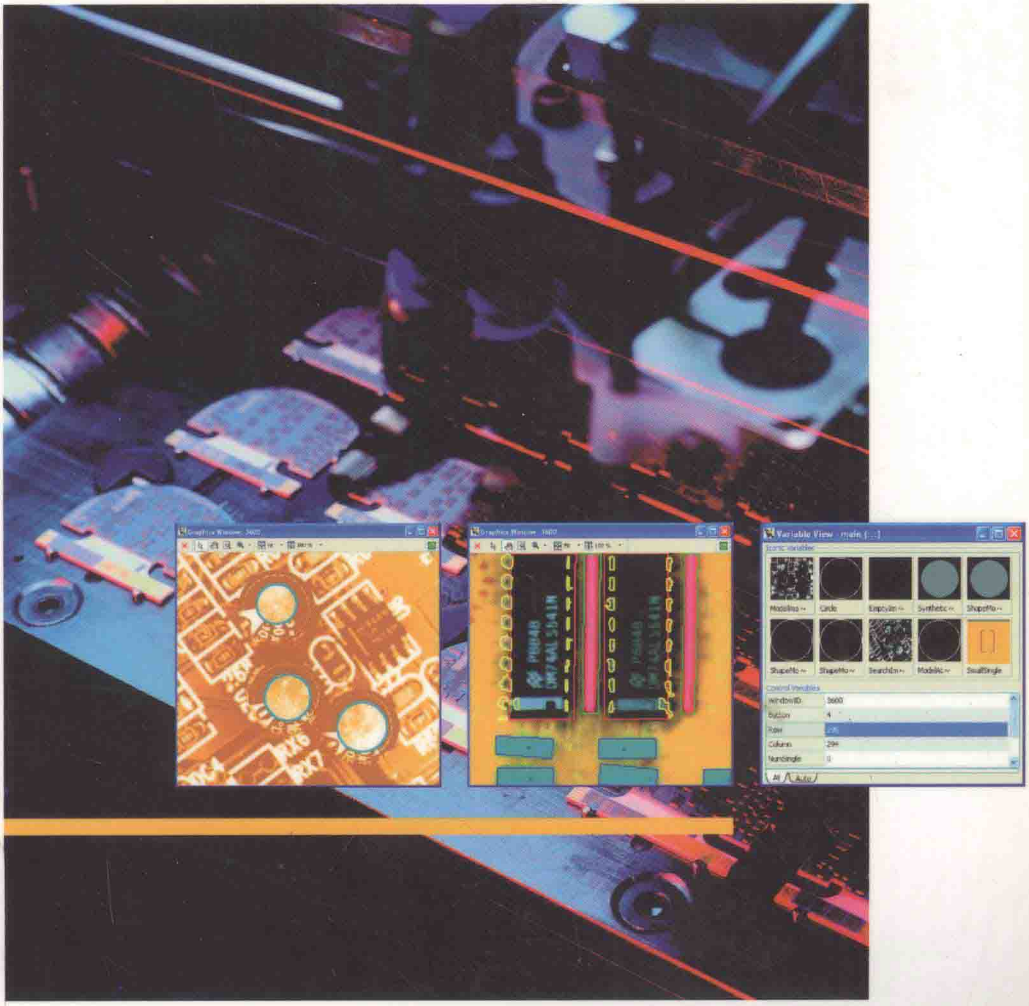
Machine Vision Algorithms and Applications



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Preface

The machine vision industry has enjoyed a growth rate well above the industry average for many years. Machine vision systems currently form an integral part of many machines and production lines. Furthermore, machine vision systems are continuously deployed in new application fields, in part because computers become faster all the time and thus enable applications to be solved that were out of reach just a few years ago.

Despite its importance, there are few books that describe in sufficient detail the technology that is important for machine vision. While there are numerous books on image processing and computer vision, very few of them describe the hardware components that are used in machine vision systems to acquire images (illuminations, lenses, cameras, and camera–computer interfaces). Furthermore, these books often only describe the theory, but not its use in real-world applications. Machine vision books, on the other hand, often do not describe the relevant theory in sufficient detail. Therefore, we feel that a book that provides a thorough theoretical foundation of all the machine vision components and machine vision algorithms, and that gives non-trivial practical examples of how they can be used in real applications, is highly overdue.

The applications we present in this book are based on the machine vision software HALCON, developed by MVTec Software GmbH. To enable you to get a hands-on experience with the machine vision algorithms and applications that we discuss, this book contains a registration code that enables you to download, free of charge, a student version of HALCON as well as all the applications we discuss. For details, please visit `www.machine-vision-book.com`.

While the focus of this book is on machine vision applications, we would like to emphasize that the principles we will present can also be used in other application fields, e.g., photogrammetry or medical image processing.

We have tried to make this book accessible to students as well as practitioners (OEMs, system integrators, and end-users) of machine vision. The text requires only very little mathematical background. We assume that the reader has a basic knowledge of linear algebra (in particular, linear transformations between vector spaces expressed in matrix algebra) and calculus (in particular, sums and differentiation and integration of one- and two-dimensional functions).

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This book is based on a lecture and lab course entitled "Machine vision algorithms" that Carsten Steger has held annually since 1999 at the Department of Informatics of Technische Universität München. Parts of the material have also been used by Markus Ulrich in a lecture entitled "Close-range photogrammetry" held annually since 2005 at the Institute of Photogrammetry and Cartography of Technische Universität München. These lectures typically draw an audience from various disciplines, e.g., computer science, photogrammetry, mechanical engineering, mathematics, and physics, which serves to emphasize the interdisciplinary nature of machine vision.

We would like to express out gratitude to several of our colleagues who have helped us in the writing of this book. Wolfgang Eckstein, Juan Pablo de la Cruz Gutiérrez, and Jens Heyder designed or wrote several of the application examples in Chapter 4. Many thanks also go to Gerhard Blahusch, Alexa Zierl, and Christoph Zierl for proofreading the manuscript. Finally, we would like to express our gratitude to Andreas Thoß and Ulrike Werner of Wiley-VCH for having the confidence that we would be able to write this book during the time HALCON 8.0 was completed.

We invite you to send us suggestions on how to improve this book. You can reach us at `authors@machine-vision-book.com`.

München, May 2007 *Carsten Steger, Markus Ulrich, Christian Wiedemann*

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1
Introduction

Machine vision is one of the key technologies in manufacturing because of increasing demands on the documentation of quality and the traceability of products. It is concerned with engineering systems, such as machines or production lines, that can perform quality inspections in order to remove defective products from production or that control machines in other ways, e.g., by guiding a robot during the assembly of a product.

Some of the common tasks that must be solved in machine vision systems are as follows [1]:

- Object identification is used to discern different kinds of objects, e.g., to control the flow of material or to decide which inspections to perform. This can be based on special identification symbols, e.g., character strings or bar codes, or on specific characteristics of the objects themselves, such as their shape.
- Position detection is used, for example, to control a robot that assembles a product by mounting the components of the product at the correct positions, e.g., in a pick-and-place machine that places electronic components onto a printed circuit board (PCB). Position detection can be performed in two or three dimensions, depending on the requirements of the application.
- Completeness checking is typically performed after a certain stage of the assembly of a product has been completed, e.g., after the components have been placed onto a PCB, to ensure that the product has been assembled correctly, i.e., that the right components are at the right place.
- Shape and dimensional inspection is used to check the geometric parameters of a product to ensure that they lie within the required tolerances. This can be used during the production process but also after a product has been in use for some time to ensure that the product still meets the requirements despite wear and tear.
- Surface inspection is used to check the surface of a finished product for imperfections such as scratches, indentations, protrusions, etc.

Figure 1.1 displays an example of a typical machine vision system. The object (1) is transported mechanically, e.g., on a conveyor belt. In machine vision applications,

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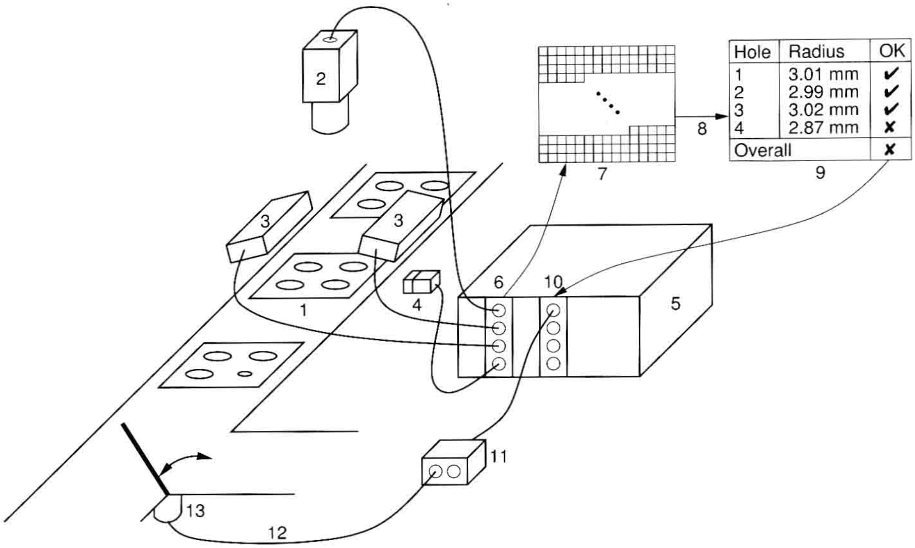

Hole	Radius	OK
1	3.01 mm	✓
2	2.99 mm	✓
3	3.02 mm	✓
4	2.87 mm	✗
Overall		✗

Fig. 1.1 The components of a typical machine vision system. An image of the object to be inspected (1) is acquired by a camera (2). The object is illuminated by the illumination (3). A photoelectric sensor (4) triggers the image acquisition. A computer (5) acquires the image through a camera–computer interface (6), in this case a frame grabber. The photoelectric sensor is connected to the frame grabber. The frame grabber triggers the strobe illumination. A device driver assembles the image (7) in the memory of the computer. The machine vision software (8) inspects the objects and returns an evaluation of the objects (9). The result of the evaluation is communicated to a programmable logic controller (PLC) (11) via a digital input/output (I/O) interface (10). The PLC controls an actuator (13) through a fieldbus interface (12). The actuator, e.g., an electric motor, moves a diverter that is used to remove defective objects from the production line.

we would often like to image the object in a defined position. This requires mechanical handling of the object and often also a trigger that triggers the image acquisition, e.g., a photoelectric sensor (4). The object is illuminated by a suitably chosen or specially designed illumination (3). Often, screens (not shown) are used to prevent ambient light from falling onto the object and thereby lowering the image quality. The object is imaged with a camera (2) that uses a lens that has been suitably selected or specially designed for the application. The camera delivers the image to a computer (5) through a camera–computer interface (6), e.g., a frame grabber. The device driver of the camera–computer interface assembles the image (7) in the memory of the computer. If the image is acquired through a frame grabber, the illumination may be controlled by the frame grabber, e.g., through strobe signals. If the camera–computer interface is not a frame grabber but a standard interface, such as IEEE 1394, USB 2.0, or Ethernet, the trigger will typically be connected to the camera and illumination directly or through a programmable logic controller (PLC). The computer can be a standard industrial PC or a specially designed computer that is directly built into the camera. The latter configuration is often called a smart camera. The computer may use a standard processor, a digital signal processor (DSP), a field-programmable gate array (FPGA), or a combination of the above. The machine vision software (8) inspects the objects and returns an evaluation of the objects (9). The result of the evaluation is communicated to a controller (11), e.g., a PLC or a distributed control system (DCS). Often, this communication is performed by digital input/output (I/O) interfaces (10). The PLC, in turn, typically controls an actuator (13) through a communication interface (12), e.g., a fieldbus or serial interface. The actuator, e.g., an electric motor, then moves a diverter that is used to remove defective objects from the production line.

As can be seen from the large number of components involved, machine vision is inherently multidisciplinary. A team that develops a machine vision system will require expertise in mechanical engineering, electrical engineering, optical engineering, and software engineering.

To maintain the focus of this book, we have made a conscious decision to focus on the aspects of a machine vision system that are pertinent to the system until the relevant information has been extracted from the image. Therefore, we will forgo a discussion of the communication components of a machine vision system that are used after the machine vision software has determined its evaluation. For more information, please consult [2, 3, 4].

In this book, we will try to give you a solid background on everything that is required to extract the relevant information from images in a machine vision system. We include the information that we wish someone had taught us when we started working in the field. In particular, we mention several idiosyncrasies of the hardware components that are highly relevant in applications, which we had to learn the hard way.

The hardware components that are required to obtain high-quality images are described in Chapter 2: illuminations, lenses, cameras, and camera–computer interfaces. We hope that, after reading this chapter, you will be able to make informed decisions about which components and setups to use in your application.

Chapter 3 discusses the most important algorithms that are commonly used in machine vision applications. It is our goal to provide you with a solid theoretical foundation that helps you in designing and developing a solution for your particular machine vision task.

To emphasize the engineering aspect of machine vision, Chapter 4 contains a wealth of examples and exercises that show how the machine vision algorithms discussed in Chapter 3 can be combined in non-trivial ways to solve typical machine vision applications.

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2
Image Acquisition

In this chapter, we will take a look at the hardware components that are involved in obtaining an image of the scene we want to analyze with the algorithms presented in Chapter 3. Illumination makes the essential features of an object visible. Lenses produce a sharp image on the sensor. The sensor converts the image into an analog or digital video signal. Finally, camera–computer interfaces (analog or digital frame grabbers, bus systems like IEEE 1394 or USB 2.0, or network interfaces like Ethernet) accept the video signal and convert it into an image in the computer's memory.

2.1
Illumination

The goal of illumination in machine vision is to make the important features of the object visible and suppress undesired features of the object. To do so, we have to consider how the light interacts with the object. One important aspect is the spectral composition of the light and the object. We can use, for example, monochromatic light on colored objects to enhance the contrast of the desired object features. Furthermore, the direction from which we illuminate the objects can be used to enhance the visibility of features. We will examine these aspects in this section.

2.1.1
Electromagnetic Radiation

Light is electromagnetic radiation of a certain range of wavelengths, as shown in Table 2.1. The range of wavelengths visible for humans is 380–780 nm. Light with shorter wavelengths is called ultraviolet (UV) light. Electromagnetic radiation with even shorter wavelengths consists of X-rays and gamma rays. Light with longer wavelengths than the visible range is called infrared (IR) light. Electromagnetic radiation with even longer wavelengths consists of microwaves and radio waves.

Monochromatic light is characterized by its wavelength λ. If light is composed of a range of wavelengths, it is often compared to the spectrum of light emitted by a black body. A black body is an object that absorbs all electromagnetic radiation that falls onto it and thus serves as an ideal source of purely thermal radiation. Therefore,

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Tab. 2.1 The light spectrum. The names of the ranges for IR and UV radiation correspond to the German standard DIN 5031 [5]. The names of the colors are due to [6].

Range	Name	Abbreviation	Wavelength λ
Ultraviolet	Vacuum UV	UV-C	100 nm–200 nm
	Far UV		200 nm–280 nm
	Middle UV	UV-B	280 nm–315 nm
	Near UV	UV-A	315 nm–380 nm
Visible	Blue-purple		380 nm–430 nm
	Blue		430 nm–480 nm
	Green-blue		480 nm–490 nm
	Blue-green		490 nm–510 nm
	Green		510 nm–530 nm
	Yellow-green		530 nm–570 nm
	Yellow		570 nm–580 nm
	Orange		580 nm–600 nm
	Red		600 nm–720 nm
	Red-purple		720 nm–780 nm
Infrared	Near IR	IR-A	780 nm–1.4 µm
		IR-B	1.4 µm–3 µm
	Middle IR	IR-C	3 µm–50 µm
	Far IR		50 µm–1 mm

the light spectrum of a black body is directly related to its temperature. The spectral radiance of a black body is given by Planck's law [7, 8]:

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} \tag{2.1}$$

Here, $c = 2.997\,924\,58 \times 10^8\,\mathrm{m\,s^{-1}}$ is the speed of light, $h = 6.626\,0693 \times 10^{-34}\,\mathrm{J\,s}$ is the Planck constant, and $k = 1.380\,6505 \times 10^{-23}\,\mathrm{J\,K^{-1}}$ is the Boltzmann constant. The spectral radiance is the energy radiated per unit wavelength by an infinitesimal patch of the black body into an infinitesimal solid angle of space. Hence, its unit is $\mathrm{W\,sr^{-1}\,m^{-2}\,nm^{-1}}$.

Figure 2.1 displays the spectral radiance for different temperatures T. It can be seen that black bodies at 300 K radiate primarily in the middle and far IR range. This is the radiation range that is perceived as heat. Therefore, this range of wavelengths is also called thermal IR. The radiation of an object at 1000 K just starts to enter the visible range. This is the red glow that can be seen first when objects are heated. For $T = 3000\,\mathrm{K}$, the spectrum is that of an incandescent lamp (see Section 2.1.2). Note that it has a strong red component. The spectrum for $T = 6500\,\mathrm{K}$ is used to represent average daylight. It defines the spectral composition of white light. The spectrum for $T = 10000\,\mathrm{K}$ produces light with a strong blue component.

Because of the correspondence of the spectra with the temperature of the black body, the spectra also define so-called color temperatures.

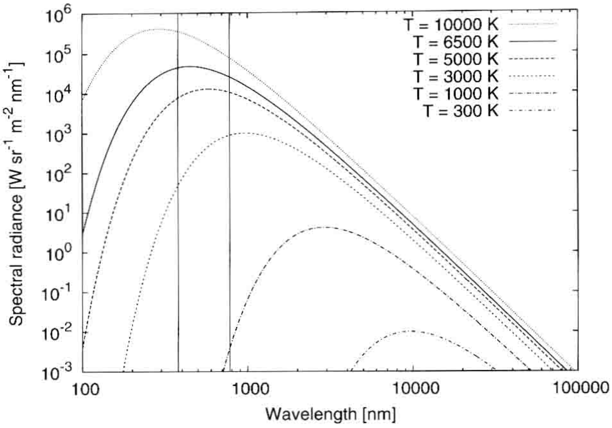

Fig. 2.1 Spectral radiance emitted by black bodies of different temperatures. The vertical lines denote the visible range of the spectrum.

2.1.2
Types of Light Sources

Before we take a look at how to use light in machine vision, we will discuss the types of light sources that are commonly used in machine vision.

Incandescent lamps create light by sending an electrical current through a thin filament, typically made of tungsten. The current heats the filament and causes it to emit thermal radiation. The heat in the filament is so high that the radiation is in the visible range of the electromagnetic spectrum. The filament is contained in a glass envelope that contains either a vacuum or a halogen gas, such as iodine or bromine, which prevents oxidation of the filament. Filling the envelope with a halogen gas has the advantage that the lifetime of the lamp is increased significantly compared to using a vacuum. The advantage of incandescent lamps is that they are relatively bright and create a continuous spectrum with a color temperature of 3000–3400 K. Furthermore, they can be operated with low voltage. One of their disadvantages is that they produce a large amount of heat: only about 5% of the power is converted to light; the rest is emitted as heat. Other disadvantages are short lifetimes and the inability to use them as flashes. Furthermore, they age quickly, i.e., their brightness decreases significantly over time.

Xenon lamps consist of a sealed glass envelope filled with xenon gas, which is ionized by electricity, producing a very bright white light with a color temperature of 5500–12 000 K. They are commonly divided into continuous-output short- and long-arc lamps as well as flash lamps. Xenon lamps can produce extremely bright flashes at a rate of more than 200 flashes per second. Each flash can be extremely short, e.g., 1–20 μs for short-arc lamps. One of their disadvantages is that they require a sophisticated and expensive power supply. Furthermore, they exhibit aging after several million flashes.

Like xenon lamps, fluorescent lamps are gas-discharge lamps that use electricity to excite mercury vapor in a noble gas, e.g., argon or neon, causing ultraviolet light to be emitted. This UV light causes a phosphor salt coated onto the inside of the tube that contains the gas to fluoresce, producing visible light. Different coatings can be chosen, resulting in different spectral distributions of the visible light, which are equivalent to color temperatures of 3000–6000 K. Fluorescent lamps are driven by alternating current. This results in a flickering of the lamp with the same frequency as the current. For machine vision, high-frequency alternating currents of 22 kHz or more must be used to avoid spurious brightness changes in the images. The main advantages of fluorescent lamps are that they are inexpensive and can illuminate large areas. Some of their disadvantages are a short lifetime, rapid aging, and an uneven spectral distribution with sharp peaks for certain frequencies. Furthermore, they cannot be used as flashes.

A light-emitting diode (LED) is a semiconductor device that produces narrow-spectrum (i.e., quasi-monochromatic) light through electroluminescence: the diode emits light in response to an electric current that passes through it. The color of the emitted light depends on the composition and condition of the used semiconductor material. The possible range of colors comprises infrared, visible, and near ultraviolet light. White LEDs can also be produced. They internally emit blue light, which is converted to white light by a coating with a yellow phosphor on the semiconductor. One advantage of LEDs is their longevity: lifetimes larger than 100 000 hours are not uncommon. Furthermore, they can be used as flashes with fast reaction times and almost no aging. Since they use direct current, their brightness can be controlled easily. In addition, they use comparatively little power and produce little heat. The main disadvantage of LEDs is that their performance depends on the ambient temperature of the environment in which they operate. The higher the ambient temperature, the lower the performance of the LED and the shorter its lifetime. However, since LEDs have so many practical advantages, they are currently the primary illumination technology used in machine vision applications.

2.1.3
Interaction of Light and Matter

Light can interact with objects in various ways, as shown in Figure 2.2.

Reflection occurs at the interfaces between different media. The microstructure of the object (essentially the roughness of its surface) determines how much of the light is reflected diffusely and how much specularly. Diffuse reflection scatters the reflected light more or less evenly in all directions. For specular reflection, the incoming and reflected light ray lie in a single plane. Furthermore, their angles with respect to the surface normal are identical. Hence, the macrostructure (shape) of the object determines the direction into which the light is reflected specularly. In practice, however, specular reflection is never perfect (as it is for a mirror). Instead, specular reflection

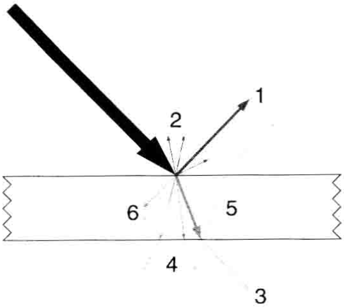

Fig. 2.2 The interaction of light with the object. The light that falls onto the object is visualized by the black arrow. (1) Specular reflection. (2) Diffuse reflection. (3) Direct transmission. (4) Diffuse transmission. (5) Backside reflection. (6) Absorption.

causes a lobe of intense reflection for certain viewing angles, depending on the angle of the incident light, as shown in Figure 2.3. The width of the side lobe is determined by the microstructure of the surface.

Reflection at metal and dielectric surfaces, e.g., glass or plastics, causes light to become partially polarized. Polarization occurs for diffuse as well as specular reflection. In practice, however, polarization caused by specular reflection dominates.

The fraction of light reflected by the surface is given by the bidirectional reflectance distribution function (BRDF). The BRDF is a function of the direction of the incoming light, the viewing direction, and the wavelength of the light. If the BRDF is integrated over both directions, the reflectivity of the surface is obtained. It depends only on the wavelength.

Note that reflection also occurs at the interface between two transparent media. This may cause backside reflections, which can lead to double images.

Transmission occurs when the light rays pass through the object. Here, the light rays are refracted, i.e., they change their direction at the interface between the different media. This is discussed in more detail in Section 2.2.2. Depending on the internal and surface structure of the object, the transmission can be direct or diffuse. The fraction of light that passes through the object is called transmittance. Like the reflectivity, it depends, among other factors, on the wavelength of the light.

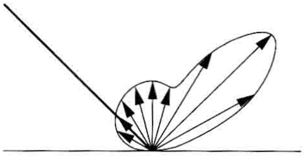

Fig. 2.3 Light distribution caused by the combination of diffuse and specular reflection.

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