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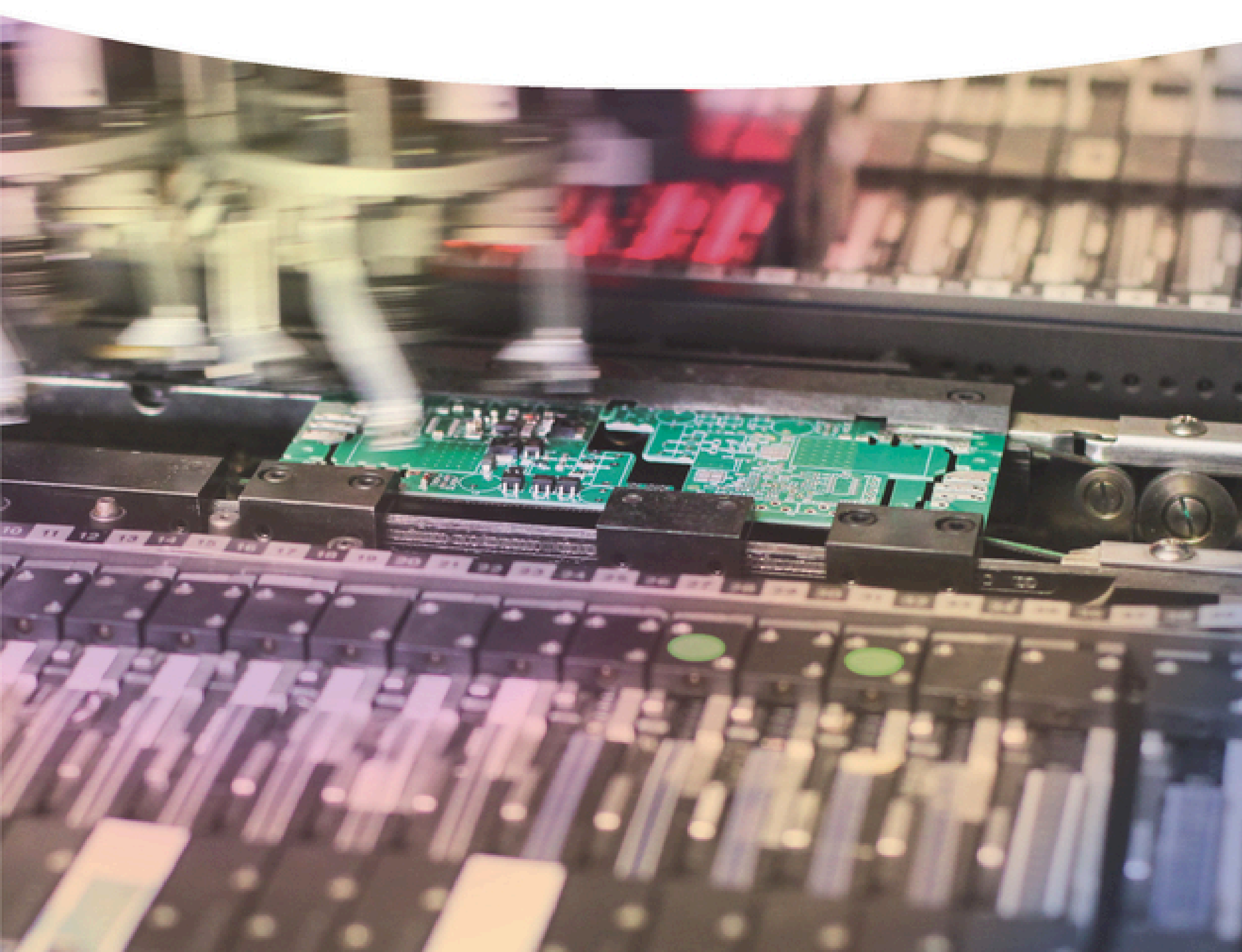
Carsten Steger, Markus Ulrich,
and Christian Wiedemann

Machine Vision Algorithms and Applications

Second Completely Revised and Enlarged Edition



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2nd, completely revised and enlarged Edition

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Authors

Dr. Carsten Steger
MVTec Software GmbH
Arnulfstraße 205
80634 München
Germany

Dr. Markus Ulrich
MVTec Software GmbH
Arnulfstraße 205
80634 München
Germany

Dr. Christian Wiedemann
MVTec SoftwareGmbH
Arnulfstraße 205
80634 München
Germany

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Contents

List of Abbreviations

ADC analog-to-digital converter. 42, 47, 52, 53, 58
AOI area of interest. 47, 74, 75
API application programming interface. 62, 72, 74, 77
APS active pixel sensor. 46

BCS base coordinate system. 324, 325, 336, 337
BGA ball grid array. 148, 157, 209, 269, 392, 393, 395–400
BRDF bidirectional reflectance distribution function. 9

CAD computer-aided design. 298, 303, 304, 308–310, 312, 314, 315, 322
CCD charge-coupled device. 11, 41–52, 54
CCIR Comité consultatif international pour la radio. 56, 57
CCS camera coordinate system. 217, 226, 228, 229, 236, 237, 242, 244, 247, 298, 305, 306, 312, 324, 325, 337, 412
CD compact disk. 134, 135, 377, 378, 380, 383
CFA color filter array. 49
CLProtocol Camera Link Protocol. 62, 73, 77
CMOS complementary metal-oxide semiconductor. 11, 41, 46–52, 54, 82
CNN convolutional neural network. 366–369
CPU central processing unit. 15, 58, 369
CWM continuous-wave-modulated. 91–95

DCS distributed control system. 2
DFT discrete Fourier transform. 123, 124
DHCP Dynamic Host Configuration Protocol. 70
DLP digital light processing. 87
DMA direct memory access. 58, 80
DMD digital micromirror device. 87–89, 258, 259
DN digital number. 42, 47, 53, 61
DPS digital pixel sensor. 47
DR dynamic range. 54
DSNU dark signal nonuniformity. 54, 55
DSP digital signal processor. 2

EIA Electronic Industries Alliance. 56, 57
EM expectation maximization. 348
EMVA European Machine Vision Association. 52, 55

FFT fast Fourier transform. 124
FPGA field-programmable gate array. 2, 61

GenApi Generic application programming interface for configuring cameras. 63, 65, 69, 73–75, 77, 79
GenCP Generic Control Protocol. 63, 69, 73, 76, 77
GenICam Generic Interface for Cameras. 62–65, 69, 71, 73–79
GenTL Generic Transport Layer. 65, 73, 77–79
GHT generalized Hough transform. 277, 279, 280, 286
GMM Gaussian mixture model. 348–350, 355, 357, 364
GPIO general-purpose input/output. 63, 64
GPU graphics processing unit. 369
GUI graphical user interface. 74, 75
GVCP GigE Vision Control Protocol. 71, 76, 77
GVSP GigE Vision Streaming Protocol. 71, 72

HTTP Hypertext Transfer Protocol. 70, 73
HVS human visual system. 48, 49, 82

I/O input/output. 2, 3, 63, 64, 71, 74
IC integrated circuit. 136, 137, 139–141, 245, 246, 252, 253, 291, 294, 369, 370
ICP iterative closest point. 319–321
ICS image coordinate system. 221, 227, 228, 236, 237, 242
IDE integrated development environment. 74
IEEE Institute of Electrical and Electronics Engineers. 2, 55, 65, 66, 70
IP Internet Protocol. 70, 72
IPCS image plane coordinate system. 219, 221, 227, 228, 232, 236, 237
IPv4 Internet Protocol, version 4. 70
IPv6 Internet Protocol, version 6. 70
IR infrared. 5, 6, 8, 11, 48, 50, 51, 92, 93, 98
IRLS iteratively reweighted least-squares. 207, 320
ISO International Organization for Standardization. 38, 39, 52

kNN *k* nearest-neighbor. 347, 449

LCD liquid-crystal display. 87
LCOS liquid crystal on silicon. 87
LED light-emitting diode. 8, 13–16, 86, 401
LLA Link-Local Address. 70
LUT lookup table. 28, 102, 107, 109, 275, 278, 279, 416
LVDS low-voltage differential signaling. 61

MCS model coordinate system. 298, 299, 305, 306, 312
MLP multilayer perceptron. 352, 354–358, 362, 364–370, 382, 438–440, 443

NCC normalized cross-correlation. 251–254, 265–267, 271, 272, 413, 438
NN nearest-neighbor. 347
NTSC National Television System Committee. 56

OCR optical character recognition. 104, 126, 127, 149, 150, 238, 302, 338, 340–343, 345, 348, 355, 365, 367, 369, 370, 377, 380, 382, 383, 438

PAL phase alternating line. 56
PC personal computer. 2, 280
PCB printed circuit board. 1, 10–12, 42, 102, 136, 137, 148, 172–175, 178, 245, 246, 264–266, 269, 270, 278, 392, 432, 434
PFNC pixel format naming convention. 64, 65, 69, 71, 73, 76, 77
PLC programmable logic controller. 2, 3
PLL phase-locked loop. 58, 59
PM pulse-modulated. 91–95
PRNU photoresponse nonuniformity. 54, 55
PTP Precision Time Protocol. 71, 72

RANSAC random sample consensus. 208, 209, 211
ReLU rectified linear unit. 366, 367
ROI region of interest. 99, 100, 102, 103, 126, 128, 136, 137, 139–141, 153, 163, 174–176, 195, 196, 263–265, 271, 272, 276, 288, 291, 292, 298, 338, 373, 375, 389, 395, 400, 401, 405, 408, 418, 422, 423, 435, 436

SAD sum of absolute gray value differences. 250–254, 263–267, 271, 275
SCARA Selective Compliant Arm for Robot Assembly. 335, 336
SED mean squared edge distance. 275, 276
SFNC standard features naming convention. 63, 65, 69, 71, 73–77, 79
SGD stochastic gradient descent. 368, 369
SLR single-lens reflex. 36
SNR signal-to-noise ratio. 52–54, 90–92, 94, 187, 188, 198, 199, 280
SSD sum of squared gray value differences. 250–254, 263, 264, 267, 271, 275
SVD singular value decomposition. 333
SVM support vector machine. 359, 361–364

TCP Transmission Control Protocol. 70
TCS tool coordinate system. 324, 325, 336
TOF time-of-flight. 82, 91–95, 322

U3VCP USB3 Vision Control Protocol. 69
U3VSP USB3 Vision Streaming Protocol. 69
UDP User Datagram Protocol. 70, 71

USB Universal Serial Bus. 2, 5, 55, 65, 67–70, 72
UV ultraviolet. 5, 6, 8, 48

WCS world coordinate system. 217, 226, 231, 232, 236–238, 256, 257, 298, 324, 398, 399, 410
WWW World Wide Web. 70

XML extensible markup language. 63, 65, 69, 71, 73, 74, 79

Preface to the Second Edition

It has been almost exactly ten years since the first edition of this book was published. Many things that we stated in the preface to the first edition of this book have remained constant. Increasing automation has continued to provide the machine vision industry with above-average growth rates. Computers have continued to become more powerful and have opened up new application areas.

On the other hand, many things have changed in the decade since the first edition was published. Efforts to standardize camera–computer interfaces have increased significantly, leading to several new and highly relevant standards. MVTec has participated in the development of many of these standards. Furthermore, sensors that acquire 3D data have become readily available in the machine vision industry. Consequently, 3D machine vision algorithms play an increasingly important role in machine vision applications, especially in the field of robotics. Machine learning (classification) is another technology that has become increasingly important.

The second edition of this book has been extended to reflect these changes. In Chapter 2, we have added a discussion of the latest camera–computer interface and image acquisition standards. Furthermore, we have included a discussion of 3D image acquisition devices. Since many of these sensors use Scheimpflug optics, we have also added a discussion of this important principle. In Chapter 3, we have extended the description of the algorithms that are used in 3D image acquisition devices to perform the 3D reconstruction. Furthermore, we describe camera models and calibration algorithms for cameras that use Scheimpflug optics. The growing importance of 3D processing is reflected by new sections on hand–eye calibration and 3D object recognition. Furthermore, the section on classification has been extended by algorithms that have become increasingly important (in particular, novelty detection and convolutional neural networks). In Chapter 4, we have added two new application examples that show how the 3D algorithms can be used to solve typical 3D applications. Overall, the book has grown by more than 35%.

The applications we present in this book are based on the machine vision software HALCON, developed by MVTec Software GmbH. To make it possible to also publish an electronic version of this book, we have changed the way by which HALCON licenses can be obtained. MVTec now provides the HALCON Student Edition for selected universities and academic research institutes. Please contact your lecturer or local distributor to find out whether you are entitled to participate in this program. Note that the student version of HALCON 8.0 is no longer available. To download the applications discussed in Chapter 4, please visit `www.machine-vision-book.com`.

The first edition of this book has been used extensively in the lectures "Image understanding I: Machine vision algorithms" given by Carsten Steger at the Department of Informatics of the Technical University of Munich, "Industrial Photogrammetry" given by Markus Ulrich at the Department of Civil, Geo, and Environmental Engineering of the Technical University of Munich, and "Industrielle Bildverarbeitung und Machine Vision" given by Markus Ulrich at the Institute of Photogrammetry and Remote Sensing of the Karlsruhe Institute of Technology. We have integrated the feedback we have received from the students into this edition of the book. A substantial part of the new material is based on the lecture "Image understanding II: Robot vision" given by Carsten Steger since 2011 at the Department of Informatics of the Technical University of Munich.

We would like to express our gratitude to several of our colleagues who have helped us in the writing of the second edition of this book. Jean-Marc Nivet provided the images in Figures 3.129–3.131 and proof-read Sections 2.5 and 3.10. Julian Beitzel supported us by preparing the pick and place example described in Section 4.14. We are also grateful to the following colleagues for proof-reading various sections of this book: Thomas Hopfner (Section 2.4), Christoph Zierl (Section 2.4), Andreas Hofhauser (Section 3.12.1), Bertram Drost (Section 3.12.3), Tobias Böttger (Section 3.13), Patrick Follmann (Sections 3.13 and 3.15.3.4), and David Sattlegger (Section 3.15.3.4). Finally, we would like to thank Martin Preuß and Stefanie Volk of Wiley-VCH who were responsible for the production of this edition of the book.

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

München, July 2017 Carsten Steger, Markus Ulrich, Christian Wiedemann

Preface to the First Edition

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 get 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 a small amount of 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), calculus (in particular, sums and differentiation and integration of one- and two-dimensional functions), Boolean algebra, and set theory.

This book is based on a lecture and lab course entitled "Machine vision algorithms" that Carsten Steger has given annually since 2001 at the Department of Informatics of the Technical University of Munich. Parts of the material have also been used by Markus Ulrich in a lecture entitled "Close-range photogrammetry" given annually since 2005 at the Institute of Photogrammetry and Cartography of the Technical University of Munich. 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 our 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

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 (Fraunhofer Allianz Vision, 2003):

- 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, such as 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 in 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, 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

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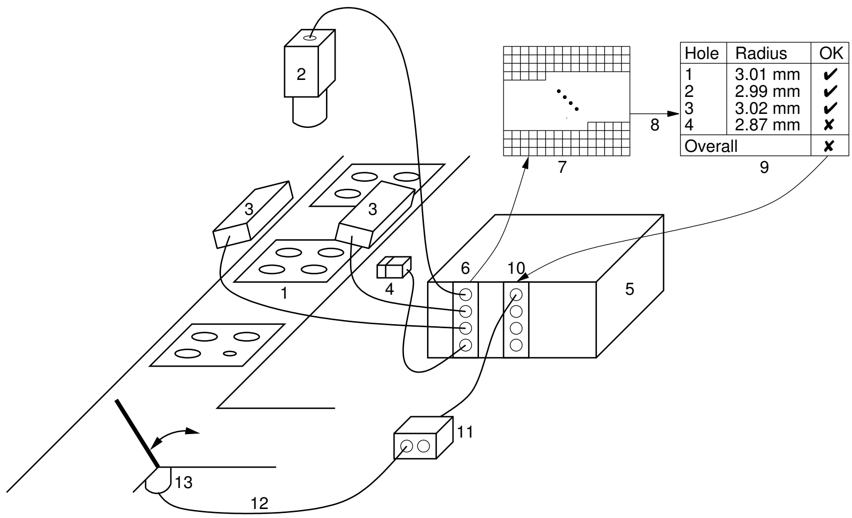

Figure 1.1 The components of a typical machine vision system. An image of the object to be inspected (1) is acquired by a camera (2). The object is illuminated by the illumination (3). A photoelectric sensor (4) triggers the image acquisition. A computer (5) acquires the image through a camera–computer 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 PLC (11) via a digital 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.

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, 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 on these aspects, please consult Caro (2003); Berge (2004); Mahalik (2003).

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: illumination, 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 will help 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.

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 a video signal. Finally, camera–computer interfaces (frame grabbers, bus systems like USB, 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 to suppress undesired features of the object. To do so, we must 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 object 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. Electromagnetic radiation with shorter wavelengths is called ultraviolet (UV) radiation. Electromagnetic radiation with even shorter wavelengths consists of X-rays and gamma rays. Electromagnetic radiation with longer wavelengths than the visible range is called infrared (IR) radiation. 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

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Table 2.1 The electromagnetic spectrum relevant for optics and photonics. The names of the ranges for IR and UV radiation correspond to ISO 20473:2007. The names of the colors for visible radiation (light) are due to Lee (2005).

Range	Name	Abbreviation	Wavelength λ
Ultraviolet	Extreme UV	–	1 nm–100 nm
	Vacuum UV	UV-C	100 nm–190 nm
	Deep UV		190 nm–280 nm
	Mid 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
	Mid IR	IR-C	3 µm–50 µm
	Far IR		50 µm–1 mm

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, 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 (Planck, 1901; Wyszecki and Stiles, 1982):

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

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 $T = 3000$ 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 $T = 6500$ K is used to represent