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 pro-

1. 简介

由于对产品质量记录及可追溯性文档的需求越来越多，机器视觉已成为生产过程中关键技术之一。在机器或生产线上，机器视觉可以检测产品质量以便将不合格产品剔除，或者指导机器人完成组装工作，因此，机器视觉与整个系统密切相关。

下面举几个常见的、必须有机器视觉系统参与的任务（Fraunhofer Allianz Vision，2003）。

- 目标识别：用来甄别不同的被测物体。比如物流控制或者根据不同目标进行不同的检测。识别可以基于特殊的识别特征，比如字符串、条码或被测物体的形状等特性。
- 位置检测：用来控制机器人在组装生产线上将产品的组件放置到正确位置。如贴片机就是将元器件放置到印刷电路板（PCB）上的正确位置。根据不同应用，位置检测可以是二维或三维的。
- 完整性检测：通常用于产品装配进行到一定阶段后。比如当元器件

duct 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.

安放于印刷电路板后要通过检测确保产品装配是正确的，也就是说正确的元器件被安放在正确的位置。

- 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.

- 形状和尺寸检测：用于检测产品的几何参数来保障其在允许的公差范围。这种检测可用于生产过程中；也可以用于产品使用一段时间之后，通过检测来确认产品经磨损后是否仍然满足要求。

- Surface inspection is used to check the surface of a finished product for imperfections such as scratches, indentations, protrusions, etc.

- 表面检测：用于检查完成的产品是否存在缺陷，如是否有划痕，是否凹凸不平等。

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 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 as-

图 1.1 为典型的机器视觉系统的例子。被测物（1）在传送带上运动，在机器视觉应用中，通常在相对固定的位置采集被测物的图像。这就要求有相应的机械部分，同时需要外触发信号来触发采集。（4）就是一种产生触发信号的光电传感器。被测物体需要合适的标准或定制光源（3）照明。通常情况下会加上遮光隔板（本例未画出）以防止环境光落到被测物体上降低图像质量。被测物的图像通过摄像机（2）及针对本应用选择或定制的合适的镜头采集得到。摄像机通过与计算机的接口（6）如图像采集卡将采集到的图像传至计算机（5），接口设备驱动程序将图像（7）放置计算机内存。如果图像采集是通过图像卡，照明可能由图像卡的闪光灯控制信号控

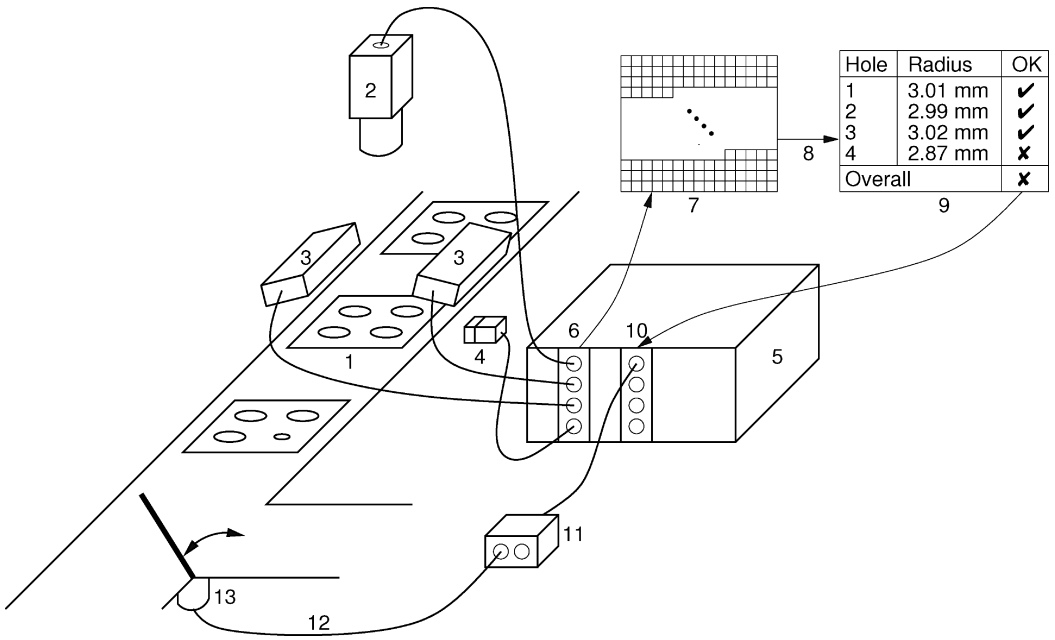

图 1.1 典型机器视觉系统组成。被测物（1）的图像由摄像机（2）获取。（3）为照明，（4）为触发图像采集的光电传感器。计算机（5）通过摄像机-计算机接口（6）获取图像，本例中接口为图像采集卡。光电传感器与图像采集卡相连接，图像采集卡触发闪光灯。驱动软件控制获取图像（7）并将图像放置计算机内存。机器视觉软件（8）检测被测物并返回检测结果（9）。通过数字 I/O （10）检测结果与 PLC（11）通信。PLC 通过现场总线接口（12）控制执行机构（13）。执行机构如电机驱动分流器将不合格被测物从生产线上剔除

sembles 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),

制。如果摄像机与计算机的接口不是图像采集卡，而是像 IEEE 1394, USB 或网络等标准接口，外触发信号通常接至摄像机和照明光源，或通过可编程逻辑控制器 PLC 完成。计算机可以是标准的工业 PC 或直接做在摄像机内部的定制计算机，后一种方式通常被称作智能摄像机。计算机可以使用标准处理器、数字信号处理器（DSP），现场可编程门阵列（FPGA）或以上几个部分合用。机器视觉软件（8）检测被测物并给出检测结果（9）。检测结果与可编程控制器（PLC）或分布式控制系统（DCS）等控制器（11）通信。通常情况下，这种通信由数字

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.

I/O 接口（10）完成。而 PLC 一般是通过通信接口（12）如现场总线或串口控制执行机构（13）。执行机构如电机则控制分流器将有问题的被测物从生产线上剔除。

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.

从机器视觉系统包含这么多部件可以看出，机器视觉的确是多学科交叉的技术。开发机器视觉系统的团队需要机械工程、电子工程、光学工程及软件工程多方面的经验。

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):

为了突出重点，本书不考虑机器视觉软件检测出结果之后的通信等部件，仅讨论至从图像中得到相关信息为止。详细系统可参考文献（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,

本书将介绍机器视觉系统从图像中得到相关信息的各个环节的背景知识。当我们开始进入这一领域时我们所需要的各种信息都包含在内。特别是我们讲到了与不同应用密切相关的硬件的一些特性，这些知识是我们必

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.

须掌握的。

第 2 章介绍了为得到高质量图像所需的硬件，包括照明、镜头、摄像机及摄像机与计算机接口。我们希望通过阅读本章节，读者可以学会在自己的应用中如何选择合适的部件及如何安装使用。

第 3 章论述了机器视觉应用中常用的重要算法，目的是使读者学到足够的理论知识，帮助读者完成特定机器视觉任务解决方案的设计和研发。

为强调机器视觉的工程应用，第 4 章以大量的实例及练习向读者展示如何将在第 3 章所讲各种机器视觉算法结合起来，解决实际的机器视觉应用问题。

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

2. 图像采集

本章将讲述为了得到被测物图像而需要的硬件部件，只有得到图像才可以使用第 3 章的算法进行分析。照明使得被测物的基本特征可见，镜头使得在传感器上得到清晰的图像，传感器将图像转换为视频信号。最后，摄像机与计算机的接口接收视频信号并将其放置到计算机内存。接口可能是图像采集卡、USB，也可能是 Ethernet 网络接口。

2.1 照明

机器视觉中照明的目的是使被测物的重要特征显现，而抑制不需要的特征。为达到此目的，我们需要考虑光源与被测物间的相互作用。其中一个重要的因素就是光源和被测物的光谱组成。我们可以用单色光照射彩色物体以增强被测物相应特征的对比度。照明的角度可以用于增强某些特征。本节将介绍上述这些内容。

2.1.1 电磁辐射

如表 2.1 所示，光是一定波长范围内的电磁辐射。人眼可视的波长范围为 380~780 nm。比此波长短的电磁辐射称作紫外线（UV）。更短的电磁

表 2.1 与光学和光子学有关的电磁波谱。红外辐射和紫外辐射的范围名称对应 ISO 20473:2007。可见光颜色名称参考 Lee（2005）。

光谱范围	名称	缩写	波长 λ
紫外线	极短紫外	–	1∼100 nm
	真空紫外	UV-C	100∼190 nm
	深紫外		190∼280 nm
	中紫外	UV-B	280∼315 nm
	近紫外	UV-A	315∼380 nm
可见光	蓝紫色		380∼430 nm
	蓝色		430∼480 nm
	绿蓝色		480∼490 nm
	蓝绿色		490∼510 nm
	绿色		510∼530 nm
	黄绿色		530∼570 nm
	黄色		570∼580 nm
	橙色		580∼600 nm
	红色		600∼720 nm
	紫红色		720∼780 nm
红外线	近红外	IR-A	780∼1.4 µm
		IR-B	1.4∼3 µm
	中波红外	IR-C	3∼50 µm
	远红外		50 µm∼1 mm

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.

辐射为 X 射线和伽马射线。比可见光波长长的电磁辐射称作红外线（IR）。比红外更长的波长的电磁辐射为微波和无线电波。

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

单色光以其波长 λ 表征。对于由多个波长组成的光，则通常将其与黑体辐射的光谱相比较。黑体可以吸收所有落到其表面的电磁辐射，因此可

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）:

以看作理想的纯热辐射源，所以黑体光谱与其温度直接相关。黑体光谱辐射符合普朗克定律（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 $\mathrm{W\,sr^{-1}\,m^{-2}\,nm^{-1}}$.

其中，$c = 2.997\,924\,58 \times 10^8\mathrm{m/s}$，为光速；$h = 6.626\,0693 \times 10^{-34}\mathrm{J \cdot s}$，为普朗克常数；$k = 1.380\,6505 \times 10^{-23}\mathrm{J/K}$，为玻尔兹曼常数。光谱辐射即为单位面积的黑体在单位立体角内、单位波长内辐射出的能量。因此，其单位为瓦特每球面平方米每纳米（$\mathrm{W \cdot sr^{-1} \cdot m^{-2} \cdot nm^{-1}}$）。

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.

图 2.1 显示了不同温度（T）下的光谱辐射。从中可以看出黑体温度在 300 K 时的辐射主要在中红外和远红外，此辐射范围就是我们感觉到的热。因此这段波长也称作热红外。1000 K 的物体辐射开始进入可见光范围，这就是当物体被加热我们首先所看到的红辉。T = 3000 K 是白炽灯的谱线（见 2.1.2 节）。注意谱线中含有很强的红的成分。T = 6500 K 用来表示日光光谱即白光的光谱。T=10000 K 为蓝光成分很强的光的谱线。

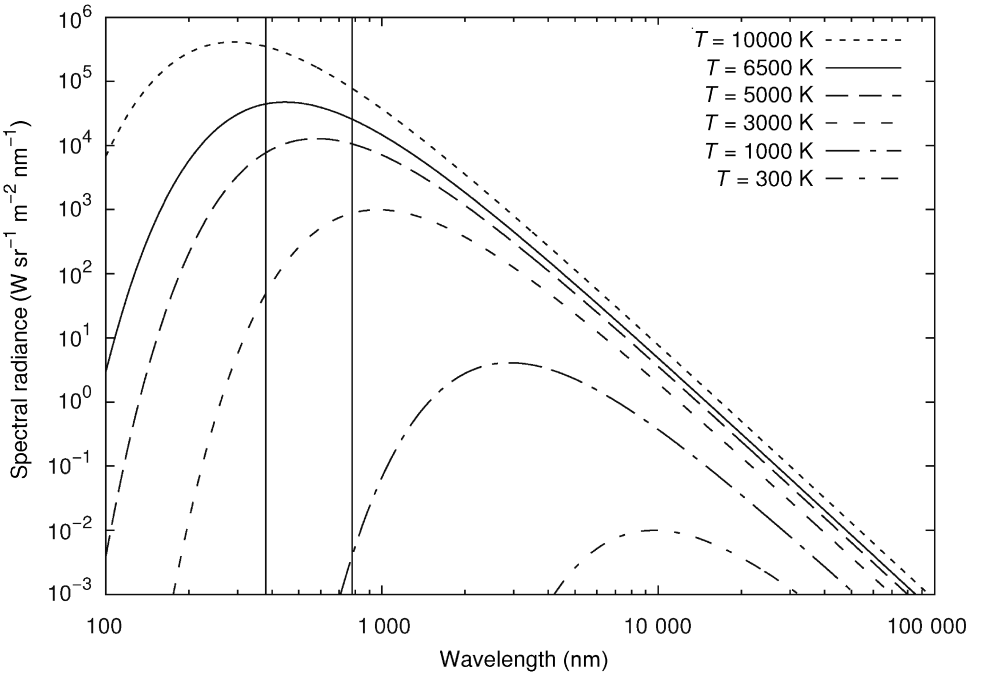

图 2.1 黑体在不同温度下的辐射光谱。两条垂直线内为可见光部分

Because of the correspondence of the spectra with the temperature of the black body, the spectra also define so-called correlated color temperatures (CIE 15:2004).

光谱与黑体温度相关，又称为色温（CIE 15:2004）。

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 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

2.1.2 光源类型

在讨论机器视觉中如何使用光源之前，首先看看在机器视觉中常用的光源有哪些。

白炽灯通过在细细的灯丝中传输电流产生光，通常情况下，灯丝是用钨制成的。电流加热灯丝使其产生热辐射。灯丝的温度非常高，其辐射在电磁辐射谱线的可见光范围内。灯丝在真空或充有卤素气体的密闭玻璃灯泡中，常见的卤素气体为碘或溴，以防止灯丝氧化。充满卤素气体比起真

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 correlated 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.

空可使灯泡的寿命大大延长。白炽灯的优点是相对较亮，而且可以产生相关联的色温为 3000~3400 K 的连续光谱。还有一个优点是白炽灯可以工作在低电压。缺点是发热严重：仅有 5% 左右的能量转换为光，其他都以热的形式散发了。另一个的缺点是寿命短，而且不能用作闪光灯。此外，白炽灯老化快，随着时间的推移，亮度迅速下降。

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 correlated 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.

氙灯是在密闭的玻璃灯泡中充上氙气，氙气被电离产生色温在 5500~12 000 K 的非常亮的白光。常被分为连续发光的短弧灯、长弧灯以及闪光灯。氙灯可做成每秒 200 多次的非常亮的闪光灯。对于短弧灯，每次亮的时间可以短至 1~20µm。氙灯的缺点是供电复杂且昂贵。此外，在几百万次闪光后会出现老化。

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 UV radiation to be emitted. This UV radiation 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 with correlated color temperatures of 3000–6000 K. Fluorescent lamps

与氙灯类似，荧光灯也是一类气体放电光源，通过电流激发在如氩、氖等惰性环境气体中的水银蒸气，产生紫外光辐射。这些紫外光辐射使得封装惰性气体的管壁上的磷盐涂层发荧光，产生可见光。使用不同的涂层，可以产生 3000~6000 K 色温的可见光。荧光灯由交流电供电，因此产生与供电相同频率的闪烁。对于机器视觉应用来说，为了避免图像明暗的变