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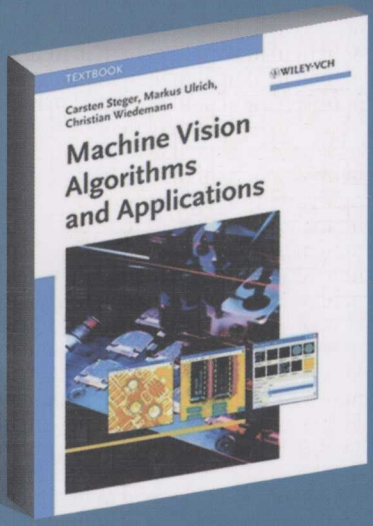
双语版

机器视觉算法与应用

Machine Vision Algorithms and Applications



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序　言

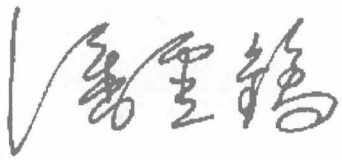
改革开放三十年来，中国经济一直呈高速发展的态势，机器视觉技术及相关产业在近年来也逐渐兴起，但尚未在中国庞大的工业体系中扮演应有的重要角色。一项调查显示，潜在客户中有近 90% 并不了解机器视觉的内容与功能。其中一个重要的原因是，中国传统制造业长期以来技术创新的簿弱和产业技术改造的滞后，对机器视觉系统这类先进技术的认识不足，没有形成迫切的需求。

当然，这种现状恰恰说明机器视觉在中国市场潜力深厚，大有可为。我们应当看到，中国的人力成本优势正在变弱，而市场上的用户对于产品质量和质量控制的要求越来越高。在这种情况下，为了保持产品质量和竞争力，制造业广泛采用机器视觉技术将是一大趋势。

机器视觉就是用机器替代人眼来完成观测和判断，常用于大批量生产过程中的产品质量检测，不适合人的危险环境和人眼视觉难以满足的场合。机器视觉可以大大提高检测精度和速度，从而提高生产效率，并且可以避免人眼视觉检测所带来的偏差和误差。

我们知道，机器视觉领域是一个重要的科学领域，也是一个技术驱动的市场。发展机器视觉，对中国的教学、科研和经济均有积极意义。为此，希望借助《机器视觉算法与应用》一书的出版，为中国机器视觉领域的广大科技工作者提供借鉴，为在校学生提供学习参考，帮助他们更快、更好地设计出满足市场和客户需求的视觉系统，为中国的经济发展做出更大贡献。

中国工程院常务副院长
中国图象图形学协会理事长　潘云鹤 院士



译者序

最近十几年，伴随着全球经济一体化进程的加速，“中国制造”已经在世界范围内发挥着越来越重要的作用。面对着用户们对产品质量更高的期待，中国的制造业在不遗余力地完善自己的技术和设备。在这种大背景下，机器视觉技术在中国进入了一个快速发展期。更多的公司在寻求利用机器视觉技术来提高生产效率，改善产品质量并降低生产成本。然而，他们都面临着一个同样的问题——尚没有一本机器视觉专著能够以工程师的视角来分析和讲解如何将这种新兴技术应用于生产实践中。

翻阅国外近20年间出版的各种计算机视觉和图像处理相关著作，我们不难发现其实并不仅仅是国内从业者会面临这样一个难题。已出版的国内外专著或是只关注“图像处理”理论，或是偏重介绍CCD/CMOS及视频原理，或是讲解“计算机图形学”相关知识，或陷入光学成像系统设计的繁杂论述中，都只是针对机器视觉技术某一方面进行偏原理性的阐述。没有任何一本书能告诉读者当需要完成一个典型的机器视觉应用——比如进行精确的2D测量时，应该如何正确地选择光源、镜头（或光学成像系统）、图像采集设备（摄像机和图像卡）来合理搭建视觉检测系统，如何对该检测系统进行标定，应该采用何种算法完成检测，如何对这些算法的速度和精度进行优化，可能影响体系测量精度的因素有哪些，以及应如何逐一克服这些影响因素以获得最佳的检测准确度和精度。

正是因为深刻洞悉广大的机器视觉从业者的困惑，德国著名机器视觉厂商MVTec联合Wiley-VCH出版公司于2007年推出了“Machine Vision Algorithms and Applications”一书。来自MVTec的专家们将自己十几年来积累下来的“实战”经验毫无保留地分享给大家。该书的三位作者不仅在MVTec公司负责著名机器视觉算法软件包HALCON的研发工作，同时还在慕尼黑工业大学（TUM）担任客座学者从事机器视觉研究教学工作，具备深厚的理论功底和实战经验。对比已有图像处理和机器视觉著作，本书具备以下三个显著特点：

- 详述了机器视觉系统的各个组成部分、部件选择和设计要点。
- 详述了各种处理算法的原理、特点、适用性、实现及优化方法。
- 针对不同行业和应用领域剖析了一些典型应用案例，并提供了大量的HALCON应用工程源码。

因此，本书不是空洞示例和晦涩数学公式的堆砌，相反，它把机器视觉技术作为一个整体来分析讨论，将各种相关技术的理论，最新进展、丰富的实例以最实用地方式进行整合，是站在机器视觉行业最前沿的专家们的经验结晶。

基于以上的认识，译者郑重向大家推荐本书。考虑到原书以英文写成，可能会给国内一部分读者造成阅读困难，为方便更多的国内机器视觉从业者和科研人员跟踪最新行业技术进展，中国大恒集团有限公司北京图像视觉技术分公司联手清华大学出版社翻译出版了本书的中英文对照版本。

翻译本书是一个艰辛的过程，个中原因在于机器视觉技术是一个多学科交叉的新兴领域，涉及到光学、数学、电子工程、计算机科学等多学科的专业名词和术语。虽然本书三位译者均来自于具有十几年行业经验的国内专业机器视觉公司——大恒图像，译者本人也具备多年的机器视觉一线从业经验，但考虑到机器视觉在中国还是一个崭新的行业，诸多技术还处在飞速发展过程中，很多英文术语尚无明确统一的中文译法，所以，为避免产生歧义

和误解，译者在中文版中保留了全部英文原文以方便读者对照。

本书第1章、第2章、第4章由杨少荣翻译，第3章由段德山和吴迪靖翻译。潘津、奚晓、罗松彬、乔军华、闫帅、王宏强、宋伟铭、刘海军、王亚鹏、杜戊、张红波、李文峰、彭晓辉、罗辉、赵栋涛、朱江兵、孙余顺等同志参加了本书的校对工作。

感谢清华大学出版社给予我们这个宝贵机会，能让我们把这本里程碑式作品的翻译奉献给各位读者。同时，感谢中国图象图形学学会在本书出版过程中给予的关注和支持。如果您对本书有何建议和意见，欢迎同我们交流讨论。

Email: info@daheng-image.com

译者

于北京

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[①], 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

前言

由于计算机的运算速度逐年增长，机器视觉在许多新的领域不断得到应用，而在几年前这些应用还无法实现。机器视觉多年来的增长速度均高于工业平均增长速度，目前机器视觉已成为许多机器和生产线的一部分。

目前市面上缺少详细介绍机器视觉技术的书籍，尽管这类书籍非常重要。已有的大量书籍介绍了图像处理及计算机视觉，但是书中对于机器视觉中获取图像的硬件部分如照明、镜头、摄像机及摄像机与计算机的接口却少有介绍，这些书籍更多的是介绍机器视觉的理论，而不是如何在现实中应用。另一方面，机器视觉的书籍对于机器视觉的相关理论又没有足够详细的介绍。因此，我们觉得一本充分介绍机器视觉硬件各个部分的理论基础及算法，同时提供如何在实际中应用的典型案例的书是非常必要的。

本书中的应用基于德国 MVTec Software GmbH 公司研发的 HALCON 软件。为了能使读者更好地掌握书中所讲机器视觉算法及应用，书中含有免费下载学生版 HALCON 软件及应用案例的注册码。更多详细信息请访

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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).

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 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. Fi-

问 `www.machine-vision-book.com`。

本书虽然重点讨论机器视觉，但是书中所讲述的原理同样可以用于如照相测量、医学图像处理等其他应用领域。

本书既适合于学生阅读，同时也适合于 OEM 厂商、系统集成商及最终用户这样的机器视觉从业者。本书仅要求读者稍有数学知识背景，对于线性代数和微积分有所了解，特别是了解以矩阵表示的矢量空间线性变换和一维、二维函数和、差分及积分。

本书主要基于 Carsten Steger 先生自 1999 年以来每年为慕尼黑科技大学信息系所作的题为"机器视觉算法"的讲座及实验课程。部分材料来源于自 2005 年起每年在慕尼黑科技大学测绘研究所 Markus Ulrich 先生所作的题为"近距离照相测量"的讲座。这些讲座的听众既有来自计算机科学、照相测量、机械工程，也有物理、数学等学科，充分体现了机器视觉的多学科交叉的本质。

在此我们要感谢 Wolfgang Eckstein, Juan Pablo de la Cruz Gutiérrez 及 Jens Heyder 设计或撰写了第 4 章部分应用案例。感谢 Gerhard Blahusch, Alexa Zierl 及 Christoph Zierl 校对原稿。最后我们衷心感谢 Wiley-VCH 出版社的Andreas Thoβ 和 Ulrike Werner,

nally, we would like to express our gratitude to Andreas Thoβ 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`.

是他们使我们在 HALOCN 8.0 研制过程中有信心完成本书。

欢迎大家就如何完善本书提出宝贵意见。

我们的联系方式
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München, May 2007

Carsten Steger, Markus Ulrich, Christian Wiedemann

目　录

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.

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。

- 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的不同检测。识别可以基于特殊的识别特征，比如字符串、条形码或被测物体的形状等特性。
- 位置探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，位置探测可以是二维的或三维的。
- 完整性检测通常用于产品装配进行到一定阶段后。比如当元器件安放于印刷电路板后要通过检测确保其产品装配是正确的，也就是说正确的元器件被安放在正确的位置。
- 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

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.

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。

- 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、凹、凸不平等。

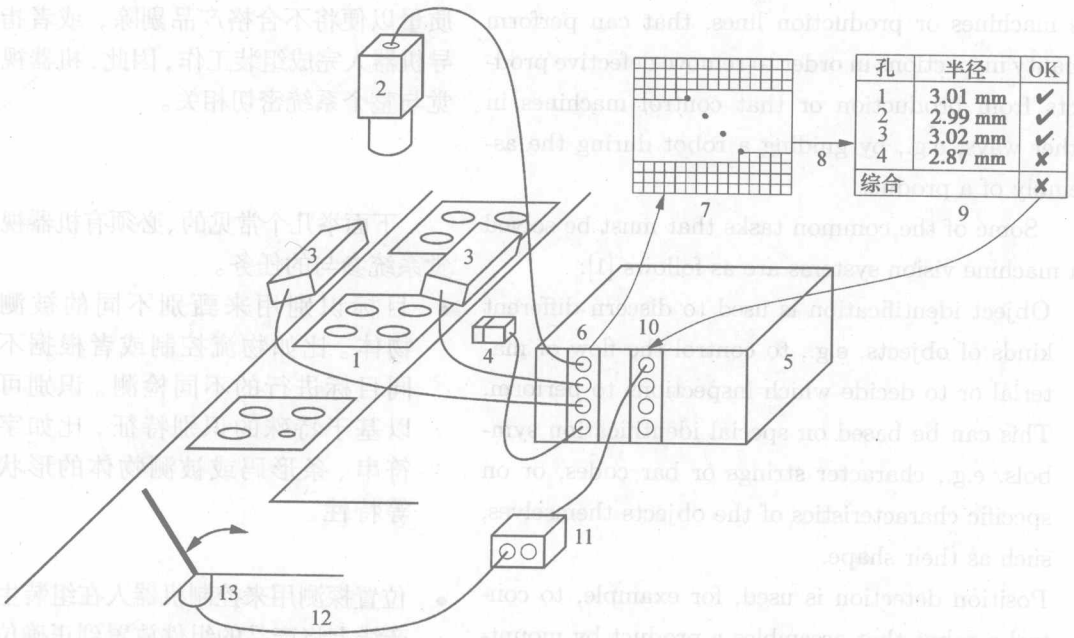

图 1.1 典型机器视觉系统组成。被测物（1）的图像由摄像机（2）获取。(3) 为照明（4）为触发图像采集的光电传感器。计算机（5）通过摄像机-计算机接口（6）获取图像，本例中接口为图像采集卡。光电传感器与图像采集卡相连接，图像采集卡触发闪光灯。驱动软件控制获取图像（7）并将图像放置计算机内存。机器视觉软件（8）检测被测物并返回检测结果（9）。通过数字I/O (10)检测结果与PLC(11)通讯。PLC通过现场总线接口（12）控制执行机构（13）。执行机构如电机驱动分流器将不合格被测物从生产线上剔除

Figure1.1 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

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

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.

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）放置于计算机内存。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 2.0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）或以上几个部分结合使用。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）通讯。通常情况下，这种通讯由数字I/O接口(10)完成。而PLC一般是通过通讯接口（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。

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等多方面的经验。

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, please consult [2, 3, 4].

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讯等部件，仅讨论至从图像中得到相关信息为止。详细信息可参考[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.

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，这些知识是我们必须掌握的。

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.

第 2 章将介绍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。

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.

第 3 章将论述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。

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.

为强调机器视觉的工程应用，第 4 章以大量的事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 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 380–780nm. Light with shorter wavelengths is called ultraviolet (UV)

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模拟或数字视频信号。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。接口可能是模拟或数字采集卡，IEEE 1394 或 USB 2.0，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。人眼可见的光称为可见光，其波长范围为380~780nm。波长比此短的光称作紫外光（UV）。更短的