清华计算机图书·译丛

Machine Vision Algorithms and Applications

Second Edition

机器视觉算法与应用

（第2版）

[德] 卡斯特恩·斯蒂格（Carsten Steger）
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杨少荣 段德山 张勇 彭潇 偏召华 译

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List of Abbreviations

缩略词

ADC analog-to-digital converter.

AOI area of interest.

API application programming interface.

APS active pixel sensor.

BCS base coordinate system.

BGA ball grid array.

BRDF bidirectional reflectance distribution function.

CAD computer-aided design.

CCD charge-coupled device.

CCIR Comité consultatif international pour la radio.

CCS camera coordinate system.

CD compact disk.

CFA color filter array.

CLP Camera Link Protocol.

CMOS complementary metal-oxide semiconductor.

CNN convolutional neural network.

CPU central processing unit.

CWM continuous-wave-modulated.

DCS distributed control system.

DFT discrete Fourier transform.

DHCP Dynamic Host Configuration Protocol.

DLP digital light processing.

DMA direct memory access.

DMD digital micromirror device.

DN digital number.

DPS digital pixel sensor.

DR dynamic range.

DSNU dark signal nonuniformity.

DSP digital signal processor.

EIA Electronic Industries Alliance.

EM expectation maximization.

EMVA European Machine Vision Association.

FFT fast Fourier transform.

FPGA field-programmable gate array.

GenApi Generic application programming interface for configuring cameras.

GenCP Generic Control Protocol.

GenICam Generic Interface for Cameras.

GenTL Generic Transport Layer.

GHT generalized Hough transform.

GMM Gaussian mixture model.

GPIO general-purpose input/output.

GPU graphics processing unit.

GUI graphical user interface.

GVCP GigE Vision Control Protocol.

GVSP GigE Vision Streaming Protocol.

HTTP Hypertext Transfer Protocol.

HVS human visual system.

I/O input/output.

IC integrated circuit.

ICP iterative closest point.

ICS image coordinate system.

IDE integrated development environment.

IEEE Institute of Electrical and Electronics Engineers.

IP Internet Protocol.

IPCS image plane coordinate system.

IPv4 Internet Protocol, version.

IPv6 Internet Protocol, version.

IR infrared.

IRLS iteratively reweighted least-squares.

ISO International Organization for Standardization.
kNN k nearest-neighbor.
LCD liquid-crystal display.
LCOS liquid crystal on silicon.
LED light-emitting diode.
LLA Link-Local Address.
LUT lookup table.
LVDS low-voltage differential signaling.
MCS model coordinate system.
MLP multilayer perceptron.
NCC normalized cross-correlation.
NN nearest-neighbor.
NTSC National Television System Committee.
OCR optical character recognition.
PAL phase alternating line.
PC personal computer.
PCB printed circuit board.
PFNC pixel format naming convention.
PLC programmable logic controller.
PLL phase-locked loop.
PM pulse-modulated.
PRNU photoresponse nonuniformity.
PTP Precision Time Protocol.
RANSAC random sample consensus.
ReLU rectified linear unit.
ROI region of interest.
SAD sum of absolute gray value differences.
SCARA Selective Compliant Arm for Robot Assembly.
SED mean squared edge distance.
SFNC standard features naming convention.
SGD stochastic gradient descent.
SLR single-lens reflex.
SNR signal-to-noise ratio.
SSD sum of squared gray value differences.
SVD singular value decomposition.
SVM support vector machine.
TCP Transmission Control Protocol.
TCS tool coordinate system.
TOF time-of-flight.
U3VCP USB3 Vision Control Protocol.
U3VSP USB3 Vision Streaming Protocol.
UDP User Datagram Protocol.
USB Universal Serial Bus.
UV ultraviolet.
WCS world coordinate system.
WWW World Wide Web.
XML extensible markup language.

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Preface to the Second Edition 第 2 版前言

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.

本书第 1 版出版差不多已经十年了。在第 1 版前言中讲的许多事情没有发生变化。日益更新的自动化技术给机器视觉工业持续带来高于平均水平的增长速度，计算机变得更加强大并且开辟了一些新的应用领域。

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.

另外一方面，自从本书第 1 版出版以来的十年中很多事情发生了变化。对标准化摄像机-计算机接口所做的努力已经显著增加，产生了许多新的且高度相关的标准。MVTec 参与了许多新标准的开发。此外，机器视觉工业领域中采集三维数据的传感器已经很容易得到，因此，三维机器视觉算法在机器视觉应用中扮演着越来越重要的角色，尤其是在机器人领域。另外一个越来越重要的技术是机器学习（分类）。

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

在本书第 2 版中扩展的内容已经体现了这些变化。在第 2 章中，我们讨论了最新的摄像机-计算机接口和图像采集标准。而且，包含了三维图像采集设备的讨论。由于这些传感器许多都用到了沙姆光学，我们也增加了对这一重要原理的讨论。在第 3 章中，扩展了三维图像采集设备用来进行三维重构的算法，此外，介绍了使用沙姆光学的摄像机模型和标定算法。为

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%.

了体现日益增长的三维图像处理的重要性，增加了新的章节：手眼标定和三维物体识别。而且，分类章节对算法进行了扩展，这些算法也变得越来越重要（尤其是，异常（新奇）检测和卷积神经网络）。在第 4 章中，增加了两个实际案例来介绍三维算法如何用于解决典型的三维应用问题。总之，本书第 2 版内容增加了 35% 以上。

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`.

本书中的应用基于德国 MVTec Software GmbH 公司开发的 HALCON 软件。为了出版本书的电子版，我们更改了 HALCON 许可的获取方式。MVTec 对挑选出的一些大学和学术研究机构提供 HALCON 学生版，请联系你的讲师或本地代理商来了解是否有权参与这个计划（是否在授权名单中）。注意 HALCON 8.0 学生版已经不再可用。要下载第 4 章中的应用案例，请访问 `www.mahine-vision-book.cn`。

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

本书第 1 版内容已经广泛用于以下讲座中，Carsten Steger 在慕尼黑科技大学信息系所开设的讲座“图像理解 I：机器视觉算法”，Markus Ulrich 在慕尼黑科技大学土木、地球和环境工程系开设的讲座“工业摄影测量法”，以及 Markus Ulrich 在卡尔

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.

斯鲁厄理工学院摄影测量与遥感研究所开设的讲座"工业图像处理和机器视觉"。我们把收到的学生反馈也整合到本书第 2 版中了，另外新资料的很大一部分基于 Carsten Steger 自从 2011 年以来在慕尼黑科技大学信息系所开设的讲座"图像理解 II：机器人视觉"。

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 4.4. 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 Bötger (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 Preuβ and Stefanie Volk of Wiley-VCH who were responsible for the production of this edition of the book.

在此我们想感谢在撰写本书第 2 版过程中提供帮助的几位同事，Jean-Marc Nivet 提供了图 3.129-3.131 中的图像并且校对了 2.5 节和 3.10 节。Julia Beitzel 帮助准备了 4.14 节机器人取放案例。我们也感谢以下同事对本书各个章节所做的校对工作：Thomas Hopfner (2.4 节), Christoph Zierl (2.4 节), Andreas Hofhauser (3.12.1 节), Bertram Drost (3.12.3 节), Tobias Böttger(3.13 节), Patrick Follmann (3.13 节和 3.15.3.4 节), 和 David Sattlegger (3.15.3.4 节)。最后，我们由衷感谢 Wiley-VCH 出版社负责本书第 2 版出版工作的 Martin Preuβ 和 Stefanie Volk。

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

欢迎大家就如何完善本书提供宝贵意见，我们的联系方式是 `authors@machine-vision-book.com`。

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

Preface to the First Edition

第 1 版前言

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.

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。

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.

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。

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

本书中的应用基于德国 MVTec Software GmbH 公司研发的 HALCON 软件。为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

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`.

应用案例的注册码。更多详细信息请访问 `www.machine-vision-book.cn`.

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.

本书虽然重点讨论机器视觉，但书中所述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。

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.

本书既适合学生，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。本书只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。

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.

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 Markus Ulrich 先生自 2005 年每年在慕尼黑科技大学测绘研究所所作的题为“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。

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 Gutiérez, 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 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.

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，是他们使我们在 HALOCN 8.0 研制过程中有信心完成本书。

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

欢迎大家就如何完善本书提出宝贵意见。我们的联系方式是 `authors@machine-vision-book.com`。

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

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