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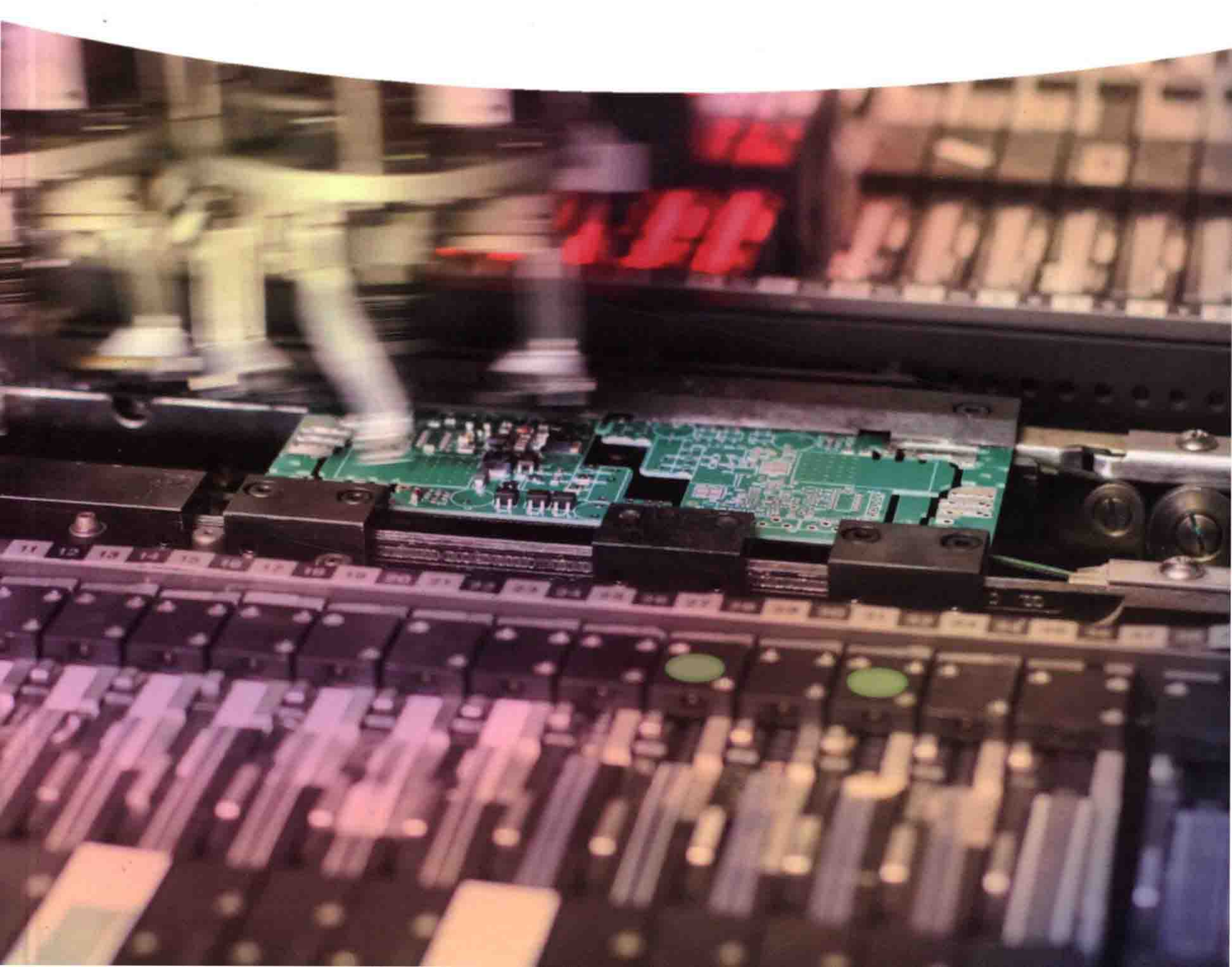
Carsten Steger, Markus Ulrich,
and Christian Wiedemann

Machine Vision Algorithms and Applications

Second, Completely Revised and Enlarged Edition



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The second edition of this successful machine vision textbook is completely updated, revised, and expanded by 35% to reflect the developments of recent years in the fields of image acquisition, machine vision algorithms and applications. The new content includes, but is not limited to, a discussion of new camera and image acquisition interfaces, 3D sensors and technologies, 3D reconstruction, 3D object recognition, and state-of-the-art classification algorithms. The authors retain their balanced approach with sufficient coverage of the theory and a strong focus on applications. All examples are based on the latest version of the machine vision software HALCON 13.

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2nd, completely revised and enlarged Edition

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Machine Vision Algorithms and Applications

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

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