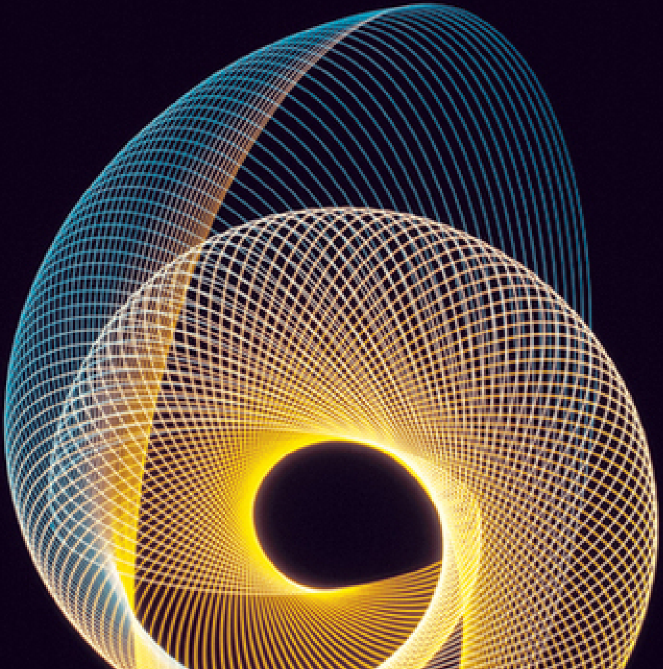
J. R. Parker

Algorithms for Image Processing and Computer Vision



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SECOND EDITION

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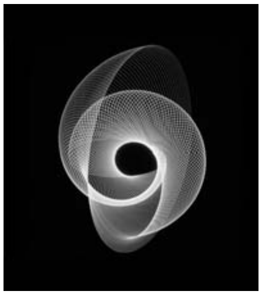

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*"Sin lies only in hurting other people unnecessarily.
All other 'sins' are invented nonsense.
(Hurting yourself is not a sin—just stupid.)"*

—Robert A. Heinlein

Thanks, Bob.

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About the Author

J.R. Parker is a computer expert and teacher, with special interests in image processing and vision, video game technologies, and computer simulations. With a Ph.D. in Informatics from the State University of Gent, Dr. Parker has taught computer science, art, and drama at the University of Calgary in Canada, where he is a full professor. He has more than 150 technical papers and four books to his credit, as well as video games such as the *Booze Cruise*, a simulation of impaired driving designed to demonstrate its folly, and a number of educational games. Jim lives on a small ranch near Cochrane, Alberta, Canada with family and a host of legged and winged creatures.

About the Technical Editor

Kostas Terzidis is an Associate Professor at the Harvard Graduate School of Design. He holds a Ph.D. in Architecture from the University of Michigan (1994), a Masters of Architecture from Ohio State University (1989), and a Diploma of Engineering from the Aristotle University of Thessaloniki (1986). His most recent work is in the development of theories and techniques for the use of algorithms in architecture. His book *Expressive Form: A Conceptual Approach to Computational Design*, published by London-based Spon Press (2003), offers a unique perspective on the use of computation as it relates to aesthetics, specifically in architecture and design. His book *Algorithmic Architecture* (Architectural Press/Elsevier, 2006) provides an ontological investigation into the terms, concepts, and processes of algorithmic architecture and provides a theoretical framework for design implementations. His latest book, *Algorithms for Visual Design* (Wiley, 2009), provides students, programmers, and researchers the technical, theoretical, and design means to develop computer code that will allow them to experiment with design problems.

Acknowledgments

Thanks this time to Sonny Chan, for the inspiration for the parallel computing chapter, to Jeff Boyd, for introducing me repeatedly to OpenCV, and to Ralph Huntsinger and Ghislain C. Vansteenkiste, for getting me into and successfully out of my Ph.D. program.

Almost all the images used in this book were created by me, using an IBM PC with a frame grabber and a Sony CCD camera, an HP scanner, and a Sony Eyetoy as a webcam. Credits for the few images that were not acquired in this way are as follows:

Corel Corporation made available the color image of the grasshopper on a leaf shown in Figure 3.33, and also was the origin of the example search images in Figure 10.5.

The sample images in Figure 10.1 were a part of the ALOI data set, use of which was allowed by J. M. Geusebroek.

Thanks to Big Hill Veterinary Clinic in Cochrane, Alberta, Canada, for the X-ray image shown in Figure 3.10e.

Finally, thanks to Dr. N. Wardlaw, of the University of Calgary Department of Geology, for the geological micropore image of Figure 3.16.

Most importantly, I need to thank my family: my wife, Katrin, and children, Bailey and Max. They sacrificed time and energy so that this work could be completed. I appreciate it and hope that the effort has been worthwhile.

Contents at a Glance

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Preface

Humans still obtain the vast majority of their sensory input through their visual system, and an enormous effort has been made to artificially enhance this sense. Eyeglasses, binoculars, telescopes, radar, infrared sensors, and photomultipliers all function to improve our view of the world and the universe. We even have telescopes in orbit (eyes outside the atmosphere) and many of those ‘‘see’’ in other spectra: infrared, ultraviolet, X-rays. These give us views that we could not have imagined only a few years ago, and in colors that we’ll never see with the naked eye. The computer has been essential for creating the incredible images we’ve all seen from these devices.

When the first edition of this book was written, the Hubble Space Telescope was in orbit and producing images at a great rate. It and the European Hipparcos telescope were the only optical instruments above the atmosphere. Now there is COROT, Kepler, MOST (Canada’s space telescope), and Swift Gamma Ray Burst Explorer. In addition, there is the Spitzer (infrared), Chandra (X-ray), GALEX (ultraviolet), and a score of others. The first edition was written on a 450-Mhz Pentium III with 256 MB of memory. In 1999, the first major digital SLR camera was placed on the market: the Nikon D1. It had only 2.74 million pixels and cost just under $6,000. A typical PC disk drive held 100–200 MB. Webcams existed in 1997, but they were expensive and low-resolution. Persons using computer images needed to have a special image acquisition card and a relatively expensive camera to conduct their work, generally amounting to $1–2,000 worth of equipment. The technology of personal computers and image acquisition has changed a lot since then.

The 1997 first edition was inspired by my numerous scans though the Internet news groups related to image processing and computer vision. I noted that some requests appeared over and over again, sometimes answered and sometimes not, and wondered if it would be possible to answer the more frequently asked questions in book form, which would allow the development of some of the background necessary for a complete explanation. However, since I had just completed a book (*Practical Computer Vision Using C*), I was in no mood to pursue the issue. I continued to collect information from the Net, hoping to one day collate it into a sensible form. I did that, and the first edition was very well received. (Thanks!)

Fifteen years later, given the changes in technology, I'm surprised at how little has changed in the field of vision and image processing, at least at the accessible level. Yes, the theory has become more sophisticated and three-dimensional vision methods have certainly improved. Some robot vision systems have accomplished rather interesting things, and face recognition has been taken to a new level. However, cheap character recognition is still, well, cheap, and is still not up to a level where it can be used reliably in most cases. Unlike other kinds of software, vision systems are not ubiquitous features of daily life. Why not? Possibly because the vision problem is really a hard one. Perhaps there is room for a revision of the original book?

My goal has changed somewhat. I am now also interested in ''democratization'' of this technology — that is, in allowing it to be used by anyone, at home, in their business, or at schools. Of course, you need to be able to program a computer, but that skill is more common than it was. All the software needed to build the programs in this edition is freely available on the Internet. I have used a free compiler (Microsoft Visual Studio Express), and OpenCV is also a free download. The only impediment to the development of your own image-analysis systems is your own programming ability.

Some of the original material has not changed very much. Edge detection, thinning, thresholding, and morphology have not been hot areas of research, and the chapters in this edition are quite similar to those in the original. The software has been updated to use Intel's OpenCV system, which makes image IO and display much easier for programmers. It is even a simple matter to capture images from a webcam in real time and use them as input to the programs. Chapter 1 contains a discussion of the basics of OpenCV use, and all software in this book uses OpenCV as a basis.

Much of the mathematics in this book is still necessary for the detailed understanding of the algorithms described. Advanced methods in image processing and vision require the motivation and justification that only mathematics can provide. In some cases, I have only scratched the surface, and have left a more detailed study for those willing to follow the references given at the ends of chapters. I have tried to select references that provide a range of approaches, from detailed and complex mathematical analyses to clear and concise exposition. However, in some cases there are very few clear descriptions in the literature, and none that do not require at least a university-level math course. Here I have attempted to describe the situation in an intuitive manner, sacrificing rigor (which can be found almost anywhere else) for as clear a description as possible. The software that accompanies the descriptions is certainly an alternative to the math, and gives a step-by-step description of the algorithms.

I have deleted some material completely from the first edition. There is no longer a chapter on wavelets, nor is there a chapter on genetic algorithms. On the other hand, there is a new chapter on classifiers, which I think was an obvious omission in the first edition. A key inclusion here is the chapter on the use of parallel programming for solving image-processing problems, including the use of graphics cards (GPUs) to accelerate calculations by factors up to 200. There's also a completely new chapter on content-based searches, which is the use of image information to retrieve other images. It's like saying, ''Find me another image that looks like this.'' Content-based search will be an essential technology over the next two decades. It will enable the effective use of modern large-capacity disk drives; and with the proliferation of inexpensive high-resolution digital cameras, it makes sense that people will be searching through large numbers of big images (huge numbers of pixels) more and more often.

Most of the algorithms discussed in this edition can be found in source code form on the accompanying web page. The chapter on thresholding alone provides 17 programs, each implementing a different thresholding algorithm. Thinning programs, edge detection, and morphology are all now available on the Internet.

The chapter on image restoration is still one of the few sources of practical information on that subject. The symbol recognition chapter has been updated; however, as many methods are commercial, they cannot be described and software can't be provided due to patent and copyright concerns. Still, the basics are there, and have been connected with the material on classifiers.

The chapter on parallel programming for vision is, I think, a unique feature of this book. Again using downloadable tools, this chapter shows how to link all the computers on your network into a large image-processing cluster. Of couse, it also shows how to use all the CPUs on your multi-core and, most importantly, gives an introductory and very practical look at how to program the GPU to do image processing and vision tasks, rather than just graphics.

Finally, I have provided a chapter giving a selection of methods for use in searching through images. These methods have code showing their implementation and, combined with other code in the book, will allow for many hours of experimenting with your own ideas and algorithms for organizing and searching image data sets.

Readers can download all the source code and sample images mentioned in this book from the book's web page — `www.wiley.com/go/jrparker`. You can also link to my own page, through which I will add new code, new images, and perhaps even new written material to supplement and update the printed matter. Comments and mistakes (how likely is that?) can be communicated through that web page, and errata will be posted, as will reader contributions to the software collection and new ideas for ways to use the code methods for compiling on other systems and with other compilers.

I invite you to make suggestions through the website for subjects for new chapters that you would like to read. It is my intention to select a popular request and to post a new chapter on that subject on the site at a future date. A book, even one primarily released on paper, need not be a completely static thing!

Jim Parker
Cochrane, Alberta, Canada
October 2010

CHAPTER

1 Practical Aspects of a Vision System—Image Display, Input/Output, and Library Calls

When experimenting with vision- and image-analysis systems or implementing one for a practical purpose, a basic software infrastructure is essential. Images consist of pixels, and in a typical image from a digital camera there will be 4–6 million pixels, each representing the color at a point in the image. This large amount of data is stored as a file in a format (such as GIF or JPEG) suitable for manipulation by commercial software packages, such as Photoshop and Paint. Developing new image-analysis software means first being able to read these files into an internal form that allows access to the pixel values. There is nothing exciting about code that does this, and it does not involve any actual image processing, but it is an essential first step. Similarly, image-analysis software will need to display images on the screen and save them in standard formats. It's probably useful to have a facility for image capture available, too. None of these operations modify an image but simply move it about in useful ways.

These bookkeeping tasks can require most of the code involved in an imaging program. The procedure for changing all red pixels to yellow, for example, can contain as few as 10 lines of code; yet, the program needed to read the image, display it, and output of the result may require an additional 2,000 lines of code, or even more.

Of course, this infrastructure code (which can be thought of as an *application programming interface*, or *API*) can be used for all applications; so, once it is developed, the API can be used without change until updates are required. Changes in the operating system, in underlying libraries, or in additional functionalities can require new versions of the API. If properly done, these new versions will require little or no modification to the vision programs that depend on it. Such an API is the *OpenCV* system.

1.1 OpenCV

OpenCV was originally developed by Intel. At the time of this writing, version 2.0 is current and can be downloaded from `http://sourceforge.net/projects/opencvlibrary/`.

However, Version 2.0 is relatively new, yet it does not install and compile with all of the major systems and compilers. All the examples in this book use Version 1.1 from `http://sourceforge.net/projects/opencvlibrary/files/opencv-win/1.1pre1/OpenCV_1.1pre1a.exe/download`, and compile with the Microsoft Visual C++ 2008 Express Edition, which can be downloaded from `www.microsoft.com/express/Downloads/#2008-Visual-CPP`.

The *Algorithms for Image Processing and Computer Vision* website (`www.wiley.com/go/jrparker`) will maintain current links to new versions of these tools. The website shows how to install both the compiler and OpenCV. The advantage of using this combination of tools is that they are still pretty current, they work, and they are free.

1.2 The Basic OpenCV Code

OpenCV is a library of C functions that implement both infrastructure operations and image-processing and vision functions. Developers can, of course, add their own functions into the mix. Thus, any of the code described here can be invoked from a program that uses the OpenCV paradigm, meaning that the methods of this book are available in addition to those of OpenCV. One simply needs to know how to call the library, and what the basic data structures of open CV are.

OpenCV is a large and complex library. To assist everyone in starting to use it, the following is a basic program that can be modified to do almost anything that anyone would want:

```
// basic.c : A `wrapper´ for basic vision programs.
#include ˝stdafx.h˝
#include ˝cv.h˝
#include ˝highgui.h˝
int main (int argc, char* argv[])
{
    IplImage *image = 0;
```

```
      image = cvLoadImage("C:\AIPCV\image1.jpg", 1 );
      if( image )
      {
          cvNamedWindow( "Input Image", 1 );
          cvShowImage( "Input Image", image );
          printf( "Press a key to exit\n");
          cvWaitKey(0);
          cvDestroyWindow("String");
      }
      else
          fprintf( stderr, "Error reading image\n" );
      return 0;
  }
```

This is similar to many example programs on the Internet. It reads in an image (`C:\AIPCV\image1.jpg` is a string giving the path name of the image) and displays it in a window on the screen. When the user presses a key, the program terminates after destroying the display window.

Before anyone can modify this code in a knowledgeable way, the data structures and functions need to be explained.

1.2.1 The IplImage Data Structure

The `IplImage` structure is the in-memory data organization for an image. Images in `IplImage` form can be converted into arrays of pixels, but `IplImage` also contains a lot of structural information about the image data, which can have many forms. For example, an image read from a GIF file could be 256 grey levels with an 8-bit pixel size, or a JPEG file could be read into a 24-bit per pixel color image. Both files can be represented as an `IplImage`.

An `IplImage` is much like other internal image representations in its basic organization. The essential fields are as follows:

`width`	An integer holding the width of the image in pixels
`height`	An integer holding the height of the image in pixels
`imageData`	A pointer to an array of characters, each one an actual pixel or color value

If each pixel is one byte, this is really all we need. However, there are many data types for an image within OpenCV; they can be bytes, ints, floats, or doubles in type, for instance. They can be greys (1 byte) or 3-byte color (RGB), 4 bytes, and so on. Finally, some image formats may have the origin at the upper left (most do, in fact) and some use the lower left (only Microsoft).

Other useful fields to know about include the following:

`nChannels`	An integer specifying the number of colors per pixel (1–4).
`depth`	An integer specifying the number of bits per pixel.
`origin`	The origin of the coordinate system. An integer: 0=upper left, 1=lower left.
`widthStep`	An integer specifying, in bytes, the size of one row of the image.
`imageSize`	An integer specifying, in bytes, the size of the image (= widthStep * height).
`imageDataOrigin`	A pointer to the origin (root, base) of the image.
`roi`	A pointer to a structure that defines a region of interest within this image that is being processed.

When an image is created or read in from a file, an instance of an `IplImage` is created for it, and the appropriate fields are given values. Consider the following definition:

```
IplImage* img = 0;
```

As will be described later in more detail, an image can be read from a file by the following code:

```
img = cvLoadImage(filename);
```

where the variable `filename` is a string holding the name of the image file. If this succeeds, then

```
img->imageData
```

points to the block of memory where the pixels can be found. Figure 1.1 shows a JPEG image named `marchA062.jpg` that can be used as an example.

Reading this image creates a specific type of internal representation common to basic RGB images and will be the most likely variant of the `IplImage` structure to be encountered in real situations. This representation has each pixel represented as three bytes: one for red, one for green, and one for blue. They appear in the order b, g, r, starting at the first row of the image and stepping through columns, and then rows. Thus, the data pointed to by `img->imageData` is stored in the following order:

$b_{0,0} \quad g_{0,0} \quad r_{0,0} \quad b_{0,1} \quad g_{0,1} \quad r_{0,1} \quad b_{0,2} \quad g_{0,2} \quad r_{0,2} \ldots$

This means that the RGB values of the pixels in the first row (row 0) appear in reverse order (b, g, r) for all pixels in that row. Then comes the next row, starting over at column 0, and so on, until the final row.