CORRELATION PATTERN RECOGNITION

Correlation is a robust and general technique for pattern recognition and is used in many applications, such as automatic target recognition, biometric recognition and optical character recognition. The design, analysis, and use of correlation pattern recognition algorithms require background information, including linear systems theory, random variables and processes, matrix/vector methods, detection and estimation theory, digital signal processing, and optical processing.

This book provides a needed review of this diverse background material and develops the signal processing theory, the pattern recognition metrics, and the practical application know-how from basic premises. It shows both digital and optical implementations. It also contains state-of-the-art technology presented by the team that developed it and includes case studies of significant current interest, such as face and target recognition.

It is suitable for advanced undergraduate or graduate students taking courses in pattern recognition theory, whilst reaching technical levels of interest to the professional practitioner.

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Preface

Mathematically, correlation is quite simply expressed. One begins with two functions $f(\bullet)$ and $g(\bullet)$, and determines their correlation as a third function $c(\bullet)$:

$$c(t) \triangleq \int_{-\infty}^{\infty} f(\tau) g^*(t+\tau)\, \mathrm{d}\tau$$

This simplicity is at the core of a rich technology in practical pattern recognition. For unit-energy signals (and images or higher-dimensional signals), the correlation output $c(t)$ achieves its maximum of 1 if and only if the signal $f(\tau)$ matches the signal $g(t+\tau)$ exactly for some t value. Thus, correlation is an important tool in determining whether the input signal or image matches a stored signal or image. However, the straightforward correlation operation (defined by the above equation) does not prove satisfactory in practical situations where the signals are not ideal and suffer any of the many distortions such as image rotations, scale changes, and noise. Over the last 20 years, the basic correlation operation has been improved to deal with these real-world challenges. The resulting body of concept, design methods, and algorithms can be aptly summarized as *correlation pattern recognition* (CPR).

Correlation pattern recognition, a subset of statistical pattern recognition, is based on selecting or creating a reference signal and then determining the degree to which the object under examination resembles the reference signal. The degree of resemblance is a simple statistic on which to base decisions about the object. We might be satisfied with deciding which class the object belongs to, or beyond that we might want more sophisticated information about which side we are viewing the object from – or conversely we might wish our pattern recognition to be quite independent of the aspect from which the object is viewed. Often it is critical to discriminate an object from classes that differ only subtly from the interesting class. Finally, the object may be embedded in (or surrounded by) clutter, some of whose characteristics may be similar to the interesting class. These considerations are at quite different levels, but the correlation algorithms create reference signals such that their correlation against the object produce statistics with direct information for those questions.

One of the principal strengths of CPR is the inherent robustness that results from its evaluating the whole signal at once. The signal is treated in a gestalt – CPR does not sweat the individual details. In contrast, feature-based techniques tend minutely to extract information from piecewise examination of the signal, and then compare the relationships among the features. By comparing the whole image against the template, CPR is less sensitive to small mismatches and obstructions.

For many years, the testing grounds for CPR have mainly been automatic target recognition (ATR) applications where correlation filters were developed to locate multiple occurrences of targets of interest (e.g., images of tanks, trucks, etc.) in input scenes. Clearly, processing speed is of interest in such applications, which has led to much interest in coherent optical correlators because of their ability to yield two-dimensional Fourier transforms (FTs) at the speed of light. However, the input and output devices in optical correlators have not progressed as fast as one would like and it is reasonable to say that today most image correlations are calculated digitally. Over the past few years, there has been a growing interest in the use of correlation filters for biometrics applications such as face recognition, fingerprint recognition, and iris recognition. In general, correlation filters should prove valuable in many image recognition applications.

Correlation can be implemented either in the time domain (space domain for images) or in the frequency domain. Because diffraction and propagation of coherent light naturally and conveniently produce the two-dimensional FT – and do so "at the speed of light" – early applications of coherent optical processing focused on correlation. This frequency domain approach is the reason for the use of the phrase "correlation filters." With the availability of the fast Fourier transform (FFT) algorithm and very high-speed digital processors, nowadays image correlations can be carried out routinely using digital implementations. In this book, we present both digital and optical processing approaches to correlation and have tried to indicate the differences and similarities. For example, in digital correlators, filter values may range more widely than in optical correlators where the optical devices impose constraints (e.g., that transmittance has to be a real value between 0 and 1). Another example is that the optical detectors detect only intensity (a real, positive value) whereas digital methods can freely produce and manipulate complex values. These differences have led to vigorous debates of the comparative advantages of digital and optical correlators and we hope that this energy has carried through to the book itself. We have enjoyed writing it.

Readers who are new to the correlation field may regard the superficial simplicity of the correlation paradigm to be anti-climactic and make no further attempt to grasp the versatility of the correlation pattern recognition techniques. Because the output from a matched filter is the cross-correlation of the received signal with the stored template, often correlation is simply misinterpreted as just matched filtering. We have sought to dispel this myth with a complete treatment of the diverse techniques for designing correlation filters that are anything but simple matched filters. It is well known that the filter theory finds widespread applications in controls, communications, adaptive signal processing, and audio and video applications. From a pattern recognition viewpoint, the same filtering concepts offer substantial benefits such as shift-invariance, graceful degradation, and avoidance of segmentation, not to mention computational simplicity (digitally or optically), and analytical closed-form solutions that yield optimal performance.

In putting together this book, our vision was to provide the reader with a single source that touches on all aspects of CPR. This field is a unique synthesis of techniques from probability and statistics, signals and systems, detection and estimation theory, and Fourier optics. As a result, the subject of CPR is rarely covered in traditional pattern recognition and computer vision books, and has remained elusive to the interested outsider.

The book begins with a practical introduction to CPR, and it ends with the current state of the art in computer-generated correlation filters. It discusses the sometimes seemingly abstract theories (e.g., detection theory, linear algebra, etc.) at the foundation of CPR, and it proceeds to applications. It presents the material necessary for a student to operate a first optical or digital correlator (aiming the level of the material at first-year graduate students in electrical engineering or optics programs). The book is intended to summarize recently published research and to put a usefully current overview of the discipline into the hands of the seasoned worker. In short, to take a line from Stuart L. Meyer, we are writing the book we would like to have owned as we began working in the field.

We believe that one of the main reasons that CPR is not used in more applications is that its practitioner must become familiar with some basic concepts in several fields: linear algebra, probability theory, linear systems theory, Fourier optics, and detection/estimation theory. Most students would not be exposed to such a mix of courses. Thus, Chapters 2, 3, and 4 in this book are devoted to providing the necessary background.

Chapter 2 reviews basic concepts in matrix/vector theory, simple quadratic optimization and probability theory, and random variables. Quadratic optimization will prove to be of importance in many correlation filter designs; e.g., when minimizing the output noise variance that is a quadratic function of the filter being designed. Similarly, basic results from probability theory, random variables, and random processes help us to determine how a filter affects the noise in the input.

As discussed before, correlation is implemented efficiently via the frequency domain. This shift-invariant implementation is based on ideas and results from the theory of linear systems, which is summarized in Chapter 3. This chapter reviews basic filtering concepts as well as the concept of sampling, an important link between continuous images and pixelated images. This chapter also introduces random signal processing, where a random signal is input to a deterministic linear, shift-invariant system.

The usual task of a pattern recognition system is to classify an input pattern into one of a finite number of classes (or hypotheses) and, if underlying statistics are known or can be modeled, we can use the results from detection theory to achieve goals such as minimizing classifier error rates or average cost. Another related topic is estimation theory, where the goal is to estimate an unknown parameter from the observations. One application of estimation is the estimation of a classifier error rate. Chapter 4 summarizes some basic concepts from detection and estimation theory.

Chapters 5 and 6 are aimed at introducing the various correlation filter designs. Chapter 5 introduces the basic correlation filters, which are aimed at recognizing a single image. It starts with the basic notion of matched filters and shows how its output is nothing but a correlation. But then the limitations of the matched filter are discussed and other alternatives such as optimal tradeoff filters (that tradeoff noise tolerance and correlation peak sharpness) are introduced. Performance metrics useful for characterizing correlation filters are introduced. Chapter 5 also introduces some correlation filter variants (e.g., binary phase-only filter) that were introduced because of optical device limitations.

Chapter 6 presents many advanced correlation filters (also called synthetic discriminant function or SDF filters), which are the correlation filters being used in many ATR and biometrics applications. In most of these advanced correlation filter designs, the main idea is to synthesize a filter from training images that exhibit the range of image distortions that the filter is supposed to accommodate. One breakthrough filter is the minimum average correlation energy (MACE) filter, which produces sharp correlation peaks and high discrimination. The MACE filter has been used with good success in ATR and biometrics applications. This and other advanced correlation filters are discussed in Chapter 6.

Chapters 7 and 8 are devoted to optical correlator implementations. Chapter 7 is aimed at introducing some basic optics concepts such as diffraction, propagation, interference, coherence, and polarization. This chapter also introduces the important topic of spatial light modulators (SLMs), which are the optical devices that convert electrical signals to optical signals. Historically, SLMs have been the limiting factors in the speed and capabilities of optical correlators. Nowadays, SLMs originally intended for the display industry are fueling a growth of small laboratory tinkering. For less than $4000, a single color television projector provides three high quality (though slow) modulators of several hundred pixels on a side, along with their necessary drive electronics. Other SLMs and architectures are becoming available whose speeds are substantially higher than the 30 frames per second for conventional broadcast television. Conventional wisdom in optical filter computation does not make appropriate use of these modulators, as is now possible using the recent algorithmic advances. Many of these SLMs are potentially very powerful but are often improperly used. The algorithms now allow us to make productive use of SLM behavior that until very recently would have been regarded as difficult and inferior. These concepts are discussed in Chapter 7.

Chapter 8 provides the mathematical details as well as the algorithms for designing correlation filters that can be implemented on limited-modulation SLMs. Unlike digital designs, these designs must carefully consider the SLM constraints right from the start. Over the past few years, significant mathematical advances (in particular, applying the minimal Euclidean distance [MED] principle) have been made in the design of such limited modulation correlation filters, the topic of Chapter 8.

Finally, Chapter 9 provides a quick review of two correlation filter applications. First is the automatic recognition of targets in synthetic aperture radar (SAR) scenes and the second is the verification of face images. Some MATLAB® code is provided to illustrate the design and application of the correlation filters.

This book would not have been possible without the help of many. At the risk of offending many others who have helped, we would like to acknowledge a few in particular. B. V. K. Vijaya Kumar (BVKVK) acknowledges Professor David Casasent of Carnegie Mellon University (CMU) for introducing him to the topic of optical computers, various colleagues and students for the many advances summarized in this book, the Electrical and Computer Engineering Department at CMU for supporting this effort through a sabbatical leave, and the Carnegie Institute of Technology for the Phil Dowd Fellowship that has accelerated the completion of this book. BVKVK also acknowledges the profound positive influences of his late parents (Ramamurthy Bhagavatula and Saradamba Bhagavatula) and the immense patience and love of his wife Latha Bhagavatula. Abhijit Mahalanobis (AM) would like to acknowledge his mother and late father for their guiding hand, and his wife for her patience in not ceasing to believe in the fact that all good things must come to an end (although this book nearly proved her wrong). Richard Juday wishes to acknowledge the support that NASA's Johnson Space Center provided through a decade and a half of his work in this field, and also the contributions of literally dozens of students, visiting faculty, post-doctoral fellows, and external colleagues. Dr. Stanley E. Monroe has been a particularly steadfast contributor, advisor, critic, and friend to all whose work has touched the Hybrid Vision Laboratory.

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