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A survey of perceptual image processing methods

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ABSTRACT

Perceptual approaches have been widely used in many areas of visual information processing. This paper presents an overview of perceptual based approaches for image enhancement, segmentation and coding. The paper also provides a brief review of image quality assessment (IQA) methods, which are used to evaluate the performance of visual information processing techniques. The intent of this paper is not to review all the relevant works that have appeared in the literature, but rather to focus on few topics that have been extensively researched and developed over the past few decades. The goal is to present a perspective as broad as possible on this actively evolving domain due to relevant advances in vision research and signal processing. Therefore, for each topic, we identify the main contributions of perceptual approaches and their limitations, and outline how perceptual vision has influenced current state-of-the-art techniques in image enhancement, segmentation, coding and visual information quality assessment.

1. Introduction

The ubiquitous use of digital visual media in our everyday life calls for the development of smarter and more efficient methods for modeling, analysing, processing and transmitting visual information. Machine vision techniques have progressed significantly to the point they are able to perform tasks that one could only dream of a few years ago; thanks to smarter algorithms, a huge increase in processing power, storage capabilities and communication bandwidth available in today's computers and networks. Nevertheless, these techniques fall short of our expectation when compared to the ease with which the human visual system (HVS) deals with complex scene analysis, processing and abstraction. Therefore, we are witnessing a growing interest in HVS inspired approaches for digital visual information modeling, analysis, processing and communication. The salient characteristics of the HVS can be exploited in the design of novel methods for image processing and machine vision. For example, the perceptual irrelevancy and visual masking effects can be exploited to improve image compression and filtering algorithms. On the other hand, the understanding of processing and coding visual information by the HVS may help one to develop new perceptual approaches that may overcome the limitations of existing signal processing based methods.

The HVS is a complex system dominated by a retinotopic organization, parallel processing, feedforward, feedback and lateral connections. This article, however, does not concern the structural or functional organization of the HVS. The focus is rather on the perceptual aspects of human vision. Section 2 introduces the main perceptual characteristics that have been largely exploited in the field of image processing. It briefly describes the concept of contrast, visual masking, contrast sensitivity function, and frequency selective channels. Section 3 presents an overview of image enhancement methods, including denoising

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techniques, contrast enhancement methods and artifact reduction approaches. Section 4 describes perceptual image segmentation algorithms and classifies them into region-based, edge-based and perceptual grouping based approaches. The improvement of image coding methods based on perceptual approaches is tackled in Section 5, focusing on perceptual lossy compression. Section 6 is dedicated to some important issues regarding quality assessment of visual information. The paper ends with some concluding remarks presented in Section 7.

2. Perceptual characteristics of the human visual system

Over many decades, the understanding of the human visual system (HVS) has attracted the curiosity of many researchers working in image processing and machine vision. Very often, however, the models used in computer vision and image processing are simplifications derived from psycho-physical experiments. In the following subsections, we describe the basic human vision characteristics that have been largely exploited in different image processing tasks such as *contrast enhancement*, *visual masking*, *contrast sensitivity function* (CSF), and *frequency* and *orientation selectivity*. The biophysical mechanisms underlying the different visual phenomena considered in this article are beyond the scope of this article. For a more comprehensive treatment of visual perception the reader is referred to [1,2].

2.1. Image contrast

Contrast is one of the most important factors to consider for image analysis and processing. However, the definition of contrast is still controversial and there is no consensus on how to define and measure objectively the perceptual contrast. For optical images, contrast refers to the ability of the human visual system to detect the luminance difference between two or more stimuli. The contrast depends on many physical and psycho-visual factors [2]. Many experiments and studies have been conducted in search for an objective contrast measure that is consistent with the perceptual sensitivity of the HVS. Weber (1834) was the first to investigate the visual discrimination ability of the HVS [2]. Many years later, Fechner (1861) formulated more explicitly the empirical law of Weber and proposed methods for measuring the discrimination ability of the HVS based on the notion of *Just Noticeable Differences* (JNDs) [2]. The first physical measure of contrast was then expressed as the relative variation of luminance. Another measure of global contrast was proposed by Michelson in 1927 [3]. This measure was introduced to quantify the visibility of optical fringes. While this contrast definition has no link with the HVS, it has been widely used in many studies, including psycho-visual experiments such as the measurement of contrast sensitivity function [4]. In 1944, Moon and Spencer considered the case of a target on a non-uniform surround and proposed a more realistic measure of contrast [5].

All these seminal experiments contributed much to our knowledge of how the HVS perceives global contrast in some limited environment. However, for natural and complex images local contrast measures need to be defined to account for non-stationarity and local structures of the signal. Since the early pioneering works of Weber and Fechner, many studies have been conducted and several measures of local contrast have been proposed, which aim to mimic the key psychophysical characteristics of the HVS [6–9]. Peli was the first to introduce frequency in the measurement of contrast in both complex and natural images. Following Peli's reasoning, Winkler and Vandergheynst proposed an isotropic contrast measure based on directional wavelet decomposition [8] to account for the energy responses of both in-phase and quadrature components. It has been shown that this new contrast measure overcomes some limitations of Peli's definition. The anisotropy selectivity of the HVS was taken into account in defining a band-limited local contrast in [10]. These studies highlighted the need for defining a contrast where both the directional and frequency selectivity are taken into account. Many other contrast measures inspired by Peli's approach have been proposed [8–11]. However, the extension of contrast measurement to color images has attracted less attention. One of the difficulties is related to the fact that the color contrast is linked to color constancy phenomenon [12], which is not well understood. A color contrast analysis based on a model of the influence of color perception and the interactions between local and global spatial structures of the image was presented in [13]. In [14], a multilevel approach based on Rizzi's method was proposed to measure perceptual contrast in color images.

Although the contributions of the chromatic channels and spatial information have been considered in the computation of local contrast, to the best of our knowledge, there is no comprehensive model that allows the prediction of global contrast from the local contrast measures; though, some attempts have been made to derive such models [11,14–16]. The basic idea of these approaches is to compute a local contrast at various spatial frequencies and then derive the global contrast by using a weighting process. However, there is no finding from the HVS or underlying visual model to support such operation. The study performed in [16] revealed also the difficulty in predicting the global impression of contrast in natural images.

2.2. Visual masking

Visual masking refers to the inability of the HVS to detect one stimulus, the target, in the presence of another, the mask. It is a perceptual phenomenon that has been studied extensively since it was first observed in the 1960s. The visibility of the target depends on many factors, in particular frequency, orientation and contrast of both the mask and the target. The modeling of this phenomenon has been carried out on some simple stimuli such as sinusoidal patterns. Legge and Foley performed extensive experiments on some simple visual scenarios [17]. They studied the threshold contrast necessary to detect the target when varying the contrast and frequency of the mask. They established an empirical power law relating