摘要

由于传统硬件设备的限制，数字图像技术广泛使用低动态范围图像，然而人眼视觉系统感知到的自然场景动态范围远远高于传统设备所能表示的最大范围，这导致了不可恢复的图像信息失真。高动态范围成像技术能够提供更广的动态范围和丰富的图像细节，更加真实地反映人眼能够观察到的亮度和色彩，吸引了学术界和工业界越来越多的关注。虽然高动态范围图像专门的成像设备已有降价趋势，但是它的显示设备价格依旧十分昂贵，一定程度上阻碍了该项技术的发展和推广应用。于是，学者们开发了多种多样的色调映射算子，将高动态范围图像转换成传统显示设备兼容的低动态范围图像，同时也被应用于高动态范围图像的后向兼容编码框架。考虑到基于低动态范围图像提出的传统质量评价方法，仅能比较相同动态范围下的两幅图像，且后向兼容编码并未高效地利用人眼视觉系统特性，因此，提出新型的针对色调映射算子的质量评价方法和研究结合视觉感知的图像编码是十分必要的。本文主要包括以下三个研究点：

第一，基于稀疏表示的色调映射质量评价模型。稀疏表示利用训练得到的过完备字典，分解图像得到稀疏系数，能够有效地表征自然图像的稀疏信号。基于稀疏域模型，提出了一种新颖的客观评价色调映射算子的度量标准(Sparse-domain Metric for Tone-mapped Images, SMTI)，包含局部特征和全局特征两个指标，来模拟人眼视觉系统对高动态范围图像和色调映射图像的感知程度。其中，局部特征又叫稀疏域结构相似性，通过抽取稀疏分解得到的图像结构信息，来衡量原始高动态范围图像和色调映射图像的结构相似度；全局特征借助自然场景统计方法，抽取稀疏系数的全局统计特性来评估色调映射图像的自然度。在公开数据集上验证本算法，实验数据表明，SMTI模型能够较准确地预测人眼视觉系统感知的色调映射图像质量。

第二，基于视觉质量评价的色调映射参数优化。构建色调映射图像的稀疏编码框架，利用色调映射质量评价模型SMTI辅助选取色调映射算子的参数最优值，用于提升色调映射图像的压缩质量。稀疏编码框架是高动态范围图像后向兼容编码的一部分，首先借助参数优化后的色调映射算子，将原高动态范围图像转换成低动态范围图像；其次，提取图像像素均值，单独采用DPCM无损编码，而残差信号将交由稀疏编码传输；残差信号通过稀疏分解得到稀疏系数，进行传统的量化和熵编码，最终与编码后的DC系数生成码流。主观和客观实验数据表明，提出的参数优化方法能够有效地提升色调映射图像的压缩效率。

第三，基于分歧归一化的稀疏编码。稀疏编码本质上是线性变换，无法去除图像

的统计冗余和感知冗余信息，而结合色调映射质量评价模型SMTI的分歧归一化可看作是非线性变换，通过引入人眼视觉系统的感知特性将稀疏系数变换到视觉均衡域，从而提升色调映射图像的稀疏编码效率。主观和客观实验数据表明，在相同的码率下，提出的方法能够明显提高编解码后重建的色调映射图像质量。

关键词：高动态范围，色调映射，稀疏表示，质量评价，图像编码

Tone-Mapping Quality Metric and Optimized Coding for High Dynamic Range Images

Lijuan Xie (Computer Applied Technology)
Directed by Siwei Ma

ABSTRACT

Limited by hardware equipment, traditional device referred technology uses low dynamic range (LDR) image formats, leading to irrecoverable losses of information as the visible range of human visual system (HVS) is much larger than the range achievable by the traditional cameras or displays. High dynamic range (HDR) technology overcomes such limitations and is able to offer high levels of immersion by adapting to the broad range of luminance levels that can be perceived by the HVS. Even if capture devices for HDR images are dropping prices, the corresponding display devices are too expensive at current stage, precluding the development of this field. To tackle this, extensive tone-mapping operators (TMOs) have been proposed in order for transforming HDR images to viewable LDR images, and also applied in the backward-compatibility based HDR image compression framework. Developing perceptually consistent image quality assessment (IQA) measures for TMO is highly desired because traditional LDR based IQA methods cannot support the cross dynamic range quality comparison. Besides, how to efficiently improve the compression performance based on the perceptual evaluation is seldom addressed. Three topics are discussed in this thesis:

At first, a novel objective quality assessment method is proposed on the basis of sparse-domain representation, which has been well advocated as a powerful tool in describing natural sparse signals with the over-complete dictionary. Specifically, two indices, incorporating both local and global features extracted from sparsely represented coefficients, are introduced to simulate the HVS characteristics on HDR images and tone-mapped images. The local feature measures the sparse-domain similarity between the pristine HDR and tone-mapped LDR images by leveraging the intrinsic structure with sparse coding. On the other hand, benefiting from the natural scene statistics (NSS), the global features are recovered from the sparse coefficients to account for the natural behaviors of tone-mapped images. Combining the local sparse-domain similarity and the global "naturalness" prior, validations on the public database

show that the proposed sparse-domain model for tone-mapped images (SMTI) provides more accurate predictions on the human perception of tone-mapped images.

Secondly, we optimize TMO parameters inspired by SMTI and then present a sparse coding framework for efficiently compressing the LDR image, which is generated from its HDR version using optimized TMO. In the proposed coding framework, given the pristine HDR image, it is converted to the LDR image by TMO. Subsequently, the DC value is extracted from LDR image and lossless encoded by DPCM coding. The residual signals are transformed by sparse coding. Then, normal quantization and entropy coding procedures are applied to compress the coefficients. Objective and subjective experiments are both conducted to evaluate the performance of the proposed method, revealing that the proposed methods outperforms the anchor.

Finally, HDR image compression efficiency is sequentially improved by perceptually optimizing the sparse coding process in terms of the proposed quality metric based on the divisive normalization mechanism. After linear sparse decomposition, divisive normalization transform (DNT) is performed as a nonlinear operation in accounting for perceptual responses in biological visual system, which aims to transform all the sparse coefficients into a perceptual uniform space. Extensive experiments have shown that the proposed scheme demonstrates great potentials in delivering better image quality for tone-mapped image coding.

KEYWORDS: High dynamic range, tone mapping, sparse representation, quality assessment, image coding