摘要

随着超高清视频内容的快速普及，视频数据量呈爆炸式增长，对存储和传输带宽提出了严峻挑战，迫切需要更加高效的视频编码技术。在混合编码框架中，变换是去除残差信号相关性的重要环节。我国自主制定的音视频编码标准（Audio Video Coding Standard，AVS）不断演进，面向下一代 AVS 标准的探索视频平台（Exploration Video Model，EVM）引入了包括解码端预测二次变换在内的多项先进编码工具，显著提升了压缩性能，但也导致编码复杂度大幅上升。同时，AVS 制作域编码的高保真模型（High Fidelity Model，HFM）作为专业制作领域的参考软件，尚未提供恒定码率控制的功能，限制了其在需要稳定码率的制作流程中的应用。本文针对上述两个问题，分别开展了编码优化研究。

基于帧内模式依赖的解码端预测二次变换：针对 EVM 中解码端预测二次变换引入三种翻转变换类型而导致率失真优化计算量大幅增加的问题，本文提出了三种低复杂度优化策略：删除对角翻转变换候选、直接帧内模式依赖优化以及交织帧内模式依赖优化。三种方法分别从全局剪枝、基于帧内预测模式区域化剪枝以及适配扩展帧内预测模式的交织剪枝的角度，有效减少了候选变换类型的数量。实验结果表明，在全帧内（All Intra，AI）配置下编码时间平均降低约 17%，在随机访问（Random Access，RA）配置下编码时间平均降低约 2%，并且编码性能几乎没有损失。所提方法已被 AVS4 探索软件 EVM 采纳。

面向制作域编码的恒定码率控制：针对 HFM 缺乏恒定码率控制功能的问题，本文设计了一套基于比例积分（Proportional Integral，PI）控制的帧级码率控制方法。该方法支持以子图或宏块为码率控制的基本单元，通过空域复杂度分级实现帧内比特的非均匀分配。并且，方法利用 PI 控制器根据实际编码码率与目标码率之间的偏差动态调整量化参数，从而实现稳定且精确的码率输出。实验结果显示，以子图为基本单元时各分量的平均性能损失控制在 4% 以内，能够满足专业制作场景对码率稳定性和存储可预测性的要求。该方法已被 AVS 制作域参考软件 HFM 采纳为码率控制方案。

最后，论文总结了超高清视频编码技术的未来发展趋势，并提出了进一步研究的方向。未来的研究包括如何在复杂视频内容和更高分辨率下更好地平衡变换编码效率与计算复杂度，以及如何实现更加智能、自适应的制作域码率控制策略。本文从变换编码的复杂度优化以及制作域的恒定码率控制两个方面，为下一代 AVS 标准的实际应用推广提供了有效的技术支撑。

关键词：AVS，视频编码，二次变换，码率控制

Research on Coding Optimization for Next Generation AVS Standard

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ABSTRACT

With the rapid spread of ultra-high-definition video content, video data volume has grown explosively, posing serious challenges to storage and transmission bandwidth. This creates an urgent need for more efficient video coding technology. In the hybrid coding framework, transform is an important step to remove correlation in residual signals. Our self-developed Audio Video Coding Standard (AVS) continues to evolve. The Exploration Video Model (EVM) for the next generation AVS standard has introduced several advanced coding tools, including decoder-side prediction secondary transform, which greatly improves compression performance but also significantly increases coding complexity. At the same time, the High Fidelity Model (HFM) for AVS production domain coding, as a reference software for professional production, does not have a constant bitrate control function, limiting its use in production workflows that require stable bitrates. This thesis addresses these two problems by carrying out coding optimization studies.

Decoder-side Prediction Secondary Transform Based on Intra Mode Dependence: To reduce the large increase in rate-distortion optimization computation caused by the three flip transform types introduced in decoder-side prediction secondary transform, this thesis proposes three low-complexity optimization strategies: removing the diagonal flip transform candidate, direct intra mode dependent optimization, and interleaved intra mode dependent optimization. These three methods reduce the number of candidate transform types by global pruning, region-based pruning using intra prediction modes, and interleaved pruning that adapts to extended intra prediction modes. Experimental results show that under the All Intra (AI) configuration, encoding time is reduced by about 17% on average, and under the Random Access (RA) configuration, encoding time is reduced by about 2% on average, with almost no loss in coding performance. The proposed methods have been adopted into the AVS4 exploration software EVM.

Constant Bitrate Control for Production Domain Encoding: To solve the problem that HFM lacks constant bitrate control, this thesis designs a frame-level bitrate control method based on Proportional Integral (PI) control. The method supports using sub-pictures or macroblocks as basic units for bitrate control, and achieves non-uniform bit allocation inside a frame by spatial complexity classification. Furthermore, the method uses a PI controller to dynamically adjust the quantization parameter based on the deviation between actual coded bitrate and target bitrate, achieving stable and accurate bitrate output. Experimental results show that when using sub-pictures as basic units, the average performance loss of each component is kept within 4%, meeting the requirements for bitrate stability and storage predictability in professional production scenarios. This method has been adopted as the bitrate control scheme for the AVS production domain reference software HFM.

Finally, the thesis summarizes future trends in ultra-high-definition video coding technology and suggests directions for further research. Future work includes how to better balance transform coding efficiency and computational complexity for complex video content and higher resolutions, and how to achieve smarter, more adaptive production domain bitrate control strategies. This thesis provides effective technical support for the practical application and promotion of the next generation AVS standard, focusing on transform coding complexity optimization and production domain constant bitrate control.

KEY WORDS: AVS, Video Coding, Secondary Transform, Bitrate Control