摘要

近几十年来，随着移动终端的飞速发展，视频的采集、处理与编辑变得更加便捷，使视频内容在统计特性、率失真特性以及时域变化等方面呈现出更强的复杂性与多样性。然而，现有码率控制方法大多针对类型相对单一、特性较为简单的视频内容设计与优化。在面对复杂多样的视频内容时，其内容自适应能力不足，出现内容表征不充分、码率控制模型失配与参数推导误差较大、全局资源分配效率不高等问题。这些问题进一步影响了码率控制方法在实际应用中的控制精度与编码效率。针对上述问题，本文以内容自适应的码率控制方法为研究主题，围绕复杂内容条件下码率控制面临的关键问题开展系统研究，旨在提升码率控制方法对内容差异和时域变化的适应能力，进而提高码率控制在实际应用中的性能。本文的主要贡献如下：

（1）本文提出了基于时空域特征引导的混合视频编码码率控制方法，针对视频内容特性分布差异扩大的问题，通过构建更有效的内容表征，提升了码率控制的内容自适应能力。对于帧内预测图像，提出了基于空域特征引导的帧内码率控制，构建了包含纹理复杂性特征与纹理规律性特征的空域特征体系，并采用支持向量回归推导帧内率失真模型。对于帧间预测图像，提出了基于时空域特征引导的帧间码率控制。针对单参考帧间预测图像，采用先分类、后模型推导的流程，基于支持向量机构建帧间类型分类器，并针对不同类型分别建立模型预测器。针对多参考帧间预测图像，提出了基于内容相似度的率失真模型推导，以适应更复杂的参考关系。在上述准确推导的率失真模型基础上，进一步提出了基于率失真模型的比特分配优化，通过优化初始比特分配，并结合模型与分配结果计算码率控制参数，实现更精准的码率控制并提升编码效率。实验结果表明，相较对比方法，该方法在码率控制精度与编码效率方面均取得了更好的性能表现。相较于 VVC 参考码率控制方法，在随机接入配置下可实现 1.99% 的码率节省并将码率误差降低 0.18%，在低延迟 B 帧配置下可实现 0.45% 的码率节省。

（2）本文提出了基于隐变量引导的神经网络视频编码码率控制方法，针对码率控制模型失配与参数推导误差增大的问题，通过更准确的模型构建与参数推导，提高了码率控制的精准度。该方法面向端到端神经网络视频编码框架，围绕帧内图像码率控制、帧间图像码率控制和比特分配三个方面开展研究。针对帧内图像，提出了基于隐变量引导的帧内图像码率控制，建立了率失真模型与码率-量化参数模型，并使用隐变量作为内容表征，以此为输入估计模型参数，从而实现内容自适应的模型推导。针对帧间图像，提出了基于在线更新的帧间图像码率控制。针对帧间图像率失真关系更为复杂的情况，建立了率失真模型与码率-量化参数模型，并进一步提出两段对数形式的

码率-量化参数模型，以提升码率控制准确性。在所建模型基础上，利用已编码帧的统计信息，并采用梯度下降方式对模型参数进行逐帧在线更新，使模型能够随视频内容变化不断调整，并用于后续帧的码率控制。对于比特分配，基于所建立的率失真模型、时域依赖和经验性约束构建了比特分配优化问题，通过进化算法高效求解帧级比特分配结果。最后，根据分配比特与码率-量化参数模型计算量化参数。实验结果表明，该方法能够实现较高精度的码率控制，平均码率误差仅为0.56%，相较对比方法平均降低超过4.18%；在相同质量条件下可实现超过8.94%的码率节省。

（3）本文提出了基于约束马尔可夫决策过程的码率控制方法，针对视频内容时域复杂性加剧的问题，通过优化全局资源分配，实现了更高效的比特分配和更高的编码效率。首先，图像组内帧级比特分配被建模为基于隐变量的约束马尔可夫决策过程。具体来说，隐变量被用于表征视频内容信息，比特预算、质量与率失真先验等被用于视频编码信息的表征。状态由视频内容信息与编码信息共同构建。动作被定义为比例调节信号，从机制上被限制输出范围。基于所构建的约束马尔可夫决策过程，进一步设计了基于强化学习的码率控制方法，以实现跨帧序列决策。为同时适配帧内预测图像与帧间预测图像，所设计的策略网络与价值网络均采用双头结构。针对策略网络，还引入了层归一化以缓解输出饱和导致的梯度消失风险，提升训练过程的稳定性。训练方法采用双延迟深度确定性策略梯度算法，并通过两组价值网络进行价值估计，以抑制高估偏差。此外，还设计了约束处理机制，包括基于比例调节的动作约束、图像组内保底分配机制以及训练样本有效性筛选机制，以保证训练与推理过程满足预算约束并提升鲁棒性。实验结果表明，该方法能够有效提升比特分配效率并进一步提升编码效率。与其他方法相比，该方法在峰值信噪比指标下至少获得平均4.86%的码率节省，在多尺度结构相似性指标下至少获得平均5.89%的码率节省。此外，得益于约束建模与约束处理机制，该方法进一步提升了码率控制精度，使平均码率误差降低至0.22%。

关键词：码率控制，内容自适应，时空域特征，隐变量，约束马尔可夫决策过程

Research on Content Adaptive Rate Control

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ABSTRACT

Over the past decades, with the rapid development of mobile devices, video acquisition, processing, and editing have become increasingly convenient, making video content exhibit greater complexity and diversity in terms of statistical characteristics, rate-distortion characteristics, and temporal variations. However, most existing rate control methods are designed and optimized for video content with relatively simple types and characteristics. When applied to complex and diverse video content, these methods tend to exhibit insufficient content adaptability and suffer from problems such as inadequate content representation, rate control model mismatch, large errors in parameter derivation, and inefficient global resource allocation. These problems further affect the rate control accuracy and coding efficiency of rate control methods in practical applications. To address these issues, this thesis focuses on content adaptive rate control methods. It systematically investigates the key challenges of rate control for complex and diverse video content. This study aims to improve the adaptability of rate control methods to content differences and temporal variations, thereby improving rate control performance in practical applications. The main contributions are summarized as follows:

(1) This thesis proposes a spatio temporal feature guided rate control method for hybrid video coding. To address the problem of enlarged differences in video content characteristic distributions, the proposed method improves the content adaptivity of rate control by constructing more effective content representations. For intra pictures, an intra rate control guided by spatial features is proposed. A spatial feature set is constructed to characterize texture complexity and texture regularity, and support vector regression is employed to derive the intra rate-distortion model. For inter pictures, an inter rate control guided by spatio temporal features is proposed. For single reference inter pictures, the proposed method first classifies picture and then derives corresponding models for different categories. An inter picture type classifier is first constructed based on support vector machines, and model predictors are then established for different picture types separately. For multi-reference inter pictures, a rate-distortion model

derivation based on content similarity is proposed to adapt to more complex reference relationships. Based on the above accurately derived rate-distortion models, a rate-distortion model based bit allocation optimization is further proposed. By optimizing the initial bit allocation and computing rate control parameters based on the models and the allocation results, the proposed method achieves more accurate rate control and improves coding efficiency. Experimental results show that, compared with competing methods, the proposed method achieves better performance in both rate control accuracy and coding efficiency. Compared with the VVC reference rate control method, it achieves 1.99% bitrate savings and reduces bitrate error by 0.18% under the random access configuration, and achieves 0.45% bitrate savings under the low delay B configuration.

(2) This thesis proposes a latent variable guided rate control method for neural video coding. To address the problems of rate control model mismatch and enlarged parameter derivation errors, the proposed method improves rate control accuracy through more accurate model construction and parameter derivation. The method is developed for end-to-end neural video coding frameworks and systematically investigates three aspects: intra rate control, inter rate control, and bit allocation. For intra pictures, a latent variable guided intra picture rate control is proposed. A rate-distortion model and a rate−quantization parameter model are established, and latent variables are used as content representations. These latent variables are then used as input to estimate the model parameters, which enables content adaptive model derivation. For inter pictures, an inter picture rate control based on online updating is proposed. To address the more complex rate-distortion relationships of inter pictures, a rate-distortion model and a rate−quantization parameter model are established, and a two-segment logarithmic rate−quantization parameter model is further proposed to improve rate control accuracy. Based on the established models, the parameters are updated online frame by frame using the statistics of previously coded frames. Gradient descent is adopted to perform the parameter update. Through this online update mechanism, the models can continuously adapt to content variation and be used for subsequent inter picture rate control. For bit allocation, an optimization problem is formulated based on the established rate-distortion models, temporal dependency, and empirical constraints. Frame level bit allocation is efficiently obtained using an evolutionary algorithm. Finally, the quantization parameter is calculated based on the allocated bits and the rate−quantization parameter model. Experiments demonstrate that the proposed method achieves highly accurate rate control, achieving an average bitrate error of only 0.56%. Compared with existing methods, it reduces the average bitrate error by more than 4.18% and

achieves over 8.94% bitrate savings under the same quality.

(3) This thesis proposes a rate control method based on a Constrained Markov Decision Process (CMDP). To address the problem of increasing temporal complexity in video content, the proposed method achieves more efficient bit allocation and higher coding efficiency by optimizing global resource allocation. First, frame level bit allocation within a group of pictures (GOP) is modeled as a latent variable based CMDP. Specifically, latent variables are used to represent video content information, while bitrate budget, quality and rate-distortion priors are used to characterize video coding information. The state is constructed jointly from the video content information and the coding information. The action is defined as a proportional adjustment signal, whose output range is constrained by design. Based on the constructed CMDP, a reinforcement learning based rate control is further designed to perform cross frame sequential decision making. To simultaneously accommodate intra and inter pictures, both the policy network and the value network adopt a dual head architecture. Layer normalization is introduced into the policy network to alleviate the risk of gradient vanishing caused by output saturation and thus improve training stability. The training method adopts the twin delayed deep deterministic policy gradient algorithm, and two value networks are used for value estimation to suppress overestimation bias. In addition, a set of constraint handling mechanisms is designed, including proportional action constraints, a GOP level minimum allocation mechanism and an effective training sample screening mechanism. These mechanisms ensure budget compliance during both training and inference, while also improving robustness. Experimental results show that the proposed method can effectively improve bit allocation efficiency and further improve coding efficiency. Compared with other methods, it achieves average bitrate savings of at least 4.86% in terms of peak signal-to-noise ratio and at least 5.89% in terms of multi-scale structural similarity. In addition, benefiting from the constrained formulation and the proposed constraint handling mechanisms, the method further improves rate control accuracy, reducing the average bitrate error to 0.22%.

KEYWORDS: Rate Control, Content Adaptive, Spatio Temporal Feature, Latent Variable, Constrained Markov Decision Process