Coding of volumetric content with MIV using VVC subpictures

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Abstract—Storage and transport of six degrees of freedom (6DoF) dynamic volumetric visual content for immersive applications requires efficient compression. ISO/IEC MPEG has recently been working on a standard that aims to efficiently code and deliver 6DoF immersive visual experiences. This standard is called the MIV, MIV uses regular 2D video codecs to code the visual data. MPEG jointly with ITU-T VCEG, has also specified the VVC standard. VVC introduced recently the concept of subpicture. This tool was specifically designed to provide independent accessibility and decodability of sub-bitstreams for omnidirectional applications. This paper shows the benefit of using subpictures in the MIV use-case. While different ways in which subpictures could be used in MIV are discussed, a particular case study is selected. Namely, subpictures are used for parallel encoding and to reduce the number of decoder instances. Experimental results show that the cost of using subpictures in terms of bitrate overhead is negligible (0.1% to 0.4%), when compared to the overall bitrate. The number of decoder instances on the other hand decreases by a factor of two.

Index Terms—6DoF, immersive video, MIV, subpicture, VVC.

I. INTRODUCTION

An immersive six degrees of freedom (6DoF) representation, unlike a three degrees of freedom (3DoF) representation, provides a larger viewing-space, where viewers have both translational and rotational freedom of movement at their disposition. In a 3DoF visual experience, content is presented to viewers as if they were positioned at the centre of a sphere, looking outwards, with all parts of the content positioned at some constant depth. Contrarily to 3DoF, 6DoF videos enable perception of motion parallax, where the relative positions of scene geometry change with the pose of the viewer. The absence of motion parallax in 3DoF videos is inconsistent with the workings of a normal human visual system and often leads to visual discomfort [1].

The large dimensions of a 6DoF viewing-space increases the amount of data required to describe the volumetric scene. Hence, the International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) Motion Picture Experts Group (MPEG) is specifying the MPEG Immersive Video (MIV) standard [2] to efficiently code dynamic volumetric visual scenes. This standard caters to virtual reality, augmented reality and mixed reality applications, such as gaming, sports broadcasting, motion picture productions, and telepresence.

MIV defines the syntax and semantics of information that enable rendering a viewport of a three-dimensional (3D) scene from associated video coded data. The standard supports scenes where the viewing-space is slightly larger than the scale of motion of a human head [3]. A viewing-space, in this context, is a 3D sub-space of the captured scene, from within which a 6DoF experience can be rendered without significant artifacts.

MIV can also accommodate volumetric scenes captured by a wide variety of multi-camera arrangements, e.g., spherical, dome, and arrays. Equirectangular Projection (ERP), perspective, and orthogonal projection formats are supported. The MIV bitstream consists of video coded data and non-video coded information related to the coded video data. Non-video coded information related to coded video data includes the projection format, camera parameters, depth Quantisation Parameters (QPs), and details of patches packed in video frames. The encoding of video data is left to regular video codecs, such as the High Efficiency Video Coding (HEVC) [4] or the Versatile Video Coding (VVC) [5].

The VVC standard, a joint effort by International Telecommunication Union - Telecommunication (ITU-T) Video Coding Experts Group (VCEG) and ISO MPEG, was finalised in July 2020. This standard has the designation H.266 in ITU-T and ISO/IEC 23090-3 in ISO/IEC. VVC is a block-based hybrid video coding scheme that can achieve 50% bitrate reduction compared to HEVC [6]. Apart from an increased coding efficiency, VVC also introduces new and versatile tools useful in a variety of applications, e.g., coding of Ultra-High Definition (UHD) video content, high dynamic range content, screen content, and omnidirectional content.

Subpicture is a new picture partitioning scheme included in VVC. A subpicture is a coded rectangular region of a picture, which is either extractable (coded independently) or non-extractable. The former can be extracted using a sub-bitstream extraction process, and can be merged with other subpicture sub-bitstreams [7]. Functionally, subpictures are similar to Motion Constrained Tile Set (MCTS) [8] in HEVC, as both allow the extraction of parts of a coded picture. Subpicture is a useful tool for 3DoF and 6DoF use-cases, where only a part of a complete scene is rendered at a given point in time.
This paper shows the benefit of utilizing subpicture in 6DoF context, particularly for coding MIV video data. Simulation results show that using the independently composable and extractable property of subpicture has negligible impact on bitrate of MIV bitstream.

The rest of the paper is organised as follows. Section II presents the related work. Sections III and IV describe the MIV standard and the VVC standard, respectively. Section V summarises how subpicture can be used in VVC. Section VI introduces the packed representation of the video coded data. Section VII shows the experimental results. Finally, Section VIII contains some final remarks.

II. RELATED WORK

VVC has been used to reduce the overall bitrate in viewport-adaptive streaming of omnidirectional video. For instance, Homayouni et al. [9] took advantage of the VVC capability of having mixed types of subpictures within a coded picture to cope with user’s head motion. In this approach, each subpicture sequence is encoded using long and short Intra Random Access Point (IRAP) periods. The long IRAP period is used on subpictures where the viewpoint change does not affect the quality, whilst the short IRAP period is used on the remaining subpictures. The capability of mixing long and short IRAP periods in the same received bitstream reduces the number of intra-coded areas in the received bitstream and thereby decreases the bitrate. Adaptive video streaming is also tackled by Carreira et al. [10], but using the Adaptive Resolution Change (ACR) concept from VVC. ACR is used to encode a Field-of-View (FoV) as multiple frames with different spatial resolution. The high resolution is destined for salient FoV, whereas low resolution is utilised for less relevant content. Another work from Carreira et al. [11] maps Cube Map Projection (CMP) to frame using the temporal scalability of VVC. Each cube face is a FoV and a frame that is encoded in a different temporal layer than other FoVs. Moreover, the defined coding structure disables the dependencies between different FoVs. On the other hand, Skupin et al. [12] introduced a rate control technique that operates at tile level. The goal in this case is to have a fair quality distribution across all tiles, for which a random forest model is used to reduce the QP variability.

Adhuran et al. [13] proposed a spherical adaptive objective function that aims to reduce redundant data in ERPs while reducing the quality loss. The objective function is minimised to derive the optimal QP, which along the function itself are used in the actual encoding process.

Other works focused on parallel processing. For example, Filipe et al. [14] proposed a slice-based splitting algorithm to balance the processing load across multiple processors. The algorithm calculates the computational complexity of a block. The estimations are used to split the 3DoF video into slices with different sizes but similar computational complexity.

The previous approaches make use of VVC to code 3DoF content. This paper focuses on how to make use of VVC and MIV to code 6DoF content.

III. THE MPEG IMMERSIVE VIDEO STANDARD

The inputs to an MIV encoder are multiple sets of videos, captured by an unordered group of real or virtual cameras having an arbitrary pose (source-views). The set of videos from each source-view represents a projection of a part of a volumetric scene onto the camera projection plane. Each video referenced from a source-view describes either projected geometry (depth) or attributes, e.g., texture, normal, and material map. The geometry video can be generated using dedicated depth sensors or computed using computer vision techniques. The technology used to capture/estimate geometry data is outside the scope of the standard.

Schematically, the MIV encoding process starts with an analysis of the video sets from source-views and their corresponding camera parameters. The analysis step involves the partitioning of the set of source-views into a set of basic-views and a set of additional-views. A basic-view, in this context, is a source-view left unmodified. Additional-views, on the other hand, are candidates considered for the pruning step that follows.

The multi-view inputs to MIV contain significant pixel level redundancies, which the pruning step exploits. In the pruning step, each pixel of the basic-views is first un-projected into the world space, and then reprojected back onto the additional-views. A pixel of an additional-view is marked to be pruned, if it is deemed to be redundant, i.e., the values of geometry and texture are very close to the values in the basic-view. The order in which additional-views are pruned is stipulated by using a hierarchical structure called the pruning tree. To keep complexity manageable, the pruning graph is generated using a greedy algorithm. The process of marking a pixel to be pruned or otherwise generates a binary mask. To preserve temporal consistency, the mask is aggregated over some number of frames. The aggregated masks then go through a process of clustering to obtain coherent spatial regions (without holes). Patches are generated from this pruning process and the resulting patches are finally packed into one or more video frames, refer to as atlases.

Atlases are compressed with a video codec, such as VVC, and stored as Visual Volumetric Video-based Coding (V3C) [15] video components. The metadata describing the patches in atlases is signalled using the V3C atlas component syntax, which provides functionalities and similar flexibility as available in many video coding specifications. For instance, it provides sequence and frame parameter sets, it may be divided into tiles, and it is encapsulated into Network Abstraction Layer (NAL) units.

In order to correctly associate V3C atlas components (i.e., encoded metadata) and V3C video components (i.e., encoded atlases), MIV stores all V3C components as a V3C sequence, which is a sequence of V3C units. A V3C unit header contains an indication of the type of data (i.e., component) to follow in V3C unit payload. Each V3C unit carries data belonging to one component (atlas or video). The first V3C unit in a V3C sequence is a V3C Parameter Set (VPS) that provides...
information about profile and level of the sequence as well mapping of video components to codecs.

The VPS also provides signalling information that allows mapping a number of V3C video components into one V3C video component, which is called the V3C packed video component.

IV. THE VERSATILE VIDEO CODING STANDARD

VVC uses a block-based hybrid video coding design, meaning the unit of processing is a block of pixels rather than the whole frame. Moreover, the coding combines predictive coding and transform coding of the prediction error.

A VVC bitstream consists of a series of NAL units, which can be Video Coding Layer (VCL) or non-VCL NAL units. VCL NAL units contain values of colour component samples. Coded data within the VCL NAL units is known as slices. Non-VCL NAL units include data different than slices, like parameter set NAL units and Supplemental Enhancement Information (SEI) NAL units.

A frame is first split into Coding Tree Units (CTUs), where a CTU is a squared region of luma and chroma samples. Next, each CTU is split into Coding Units (CUs) using a multi-type tree that considers quad-tree, binary, and tertiary trees. Each CU is further split until the minimum supported size is reached. A CU is the basic processing unit for operations such as predictive coding and transform coding. Predictive coding removes redundancies within a frame (spatial) and between frames (temporal). Transform coding decorrelates the prediction error so less important coefficients can be discarded.

The high-level partitioning of a frame is composed of slices, tiles, and subpictures, each comprising a number of complete CTUs. A slice contains coded content that can be reconstructed independently from other slices within the same frame, mostly since in-frame prediction and entropy coding dependencies are disabled across the slice boundaries. The same applies to tiles, which specify horizontal and vertical boundaries and split a frame into columns and rows. Additionally, each tile can be processed by a single processor core. Finally, subpicture is a rectangular set of slices that can be decoded independently of other subpictures (marked as extractable).

Subpictures have the following properties. First, the encoder can determine the subpicture boundaries to be treated like picture boundaries in inter prediction. Consequently, the samples at subpicture boundaries are padded when motion vectors reference sample locations outside subpicture boundaries. Second, independent subpictures can be extracted from their source bitstream and merged into a destination bitstream without the need for rewriting slice headers. Third, subpictures of the same coded picture need not have the same VCL NAL unit type. This enables extracting a first set of subpictures from an IRAP picture and a second set of subpictures from a non-IRAP picture and merging both sets into the same coded picture in a destination bitstream.

V. WAYS TO USE SUBPICTURES IN MIV

Subpicture allows the creation of efficient bitstream with independently extractable parts. The signalling overhead to indicate the independent accessibility is marginal, considering the large amounts of data that is to be coded. The use of subpicture allows: (1) viewport-dependent decoding and rendering; (2) scalable rendering of either a 3DoF or 6DoF variation of the content from a single bitstream; (3) parallel encoding of atlases; and (4) minimising the number of streams to be synchronously decoded and rendered.

A viewport of an omnidirectional picture/sequence is the rectilinear projection of the contents in the scene that is presented to a viewer. The portion of a scene that is outside the viewport is not rendered for display. In an ideal case, only the parts of the bitstream that are in the viewport require decoding and rendering. However, practically, at least a low quality version of the bitstream is also made available to the client, to account for unpredictable viewer head motion. Since, minimally, only the viewport is required to be decoded and rendered at high quality, subpictures can be used to partition the omnidirectional visual field. For example, an omnidirectional scene can be projected using CMP, and each cube face can be coded as a subpicture. Consequently, only the subpictures that fall in the viewport are required to be decoded and rendered, reducing the computational resources needed.

Immersive video is still an active field of research and commercial product development. Presently, a majority of display devices can only render 3DoF video. The MIV specification is flexible to allow generating bitstreams to cater to both 3DoF as well as a 6DoF capable devices. An atlas can be created such that one subpicture of the atlas represents a full ERP image/video captured by one of the cameras, and the remaining subpictures represents the additional depth information and patches required for 6DoF viewing.

Fig. 1 illustrates a frame of an atlas that is created in this manner. The independently extractable property of a subpicture would allow either a network element, e.g. an edge computing server, or a even a client device to choose the subpicture that is required for proper rendering of a viewport. Players that only support 3DoF video can identify the ERP texture part of the decoded pictures using the region-wise packing information that can be present in the video bitstream as a supplemental enhancement information message and/or in the file metadata specified in the Omnidirectional Media Format (OMAF) [16]. Consequently, upgrading immersive video services with MIV and 6DoF rendering can be done.
without comprising the compatibility with legacy players and devices only supporting 3DoF 360° video.

A video encoder is complex, and encoding a frame of video can take a non-trivial duration of time. Parallelism in video coding is not a new concept and there are several tools that have been specified (wavefront parallel processing, tiles, etc.). By using parallelism, the rendered output of the volumetric video is going to be incorrect. This problem can be handled by making the decoded frames available in advance, which would require client-side buffering. However, memory is a limited resource, especially in low-power mobile devices. Therefore, reducing the number of coded bitstreams to be decoded would help with this synchronisation problem. In section VI, it is shown that by packing an atlas with both the texture and geometry components, a single decoder can be used, thus solving the synchronisation problem.

VI. PACKED REPRESENTATION OF AN ATLAS

The goal is to reduce the number of VVC decoder instances required to reconstruct the compressed MIV atlases. For that purpose, texture and geometry atlases are encoded with constraints that allow to combine them into one bitstream, where each of them represents a single sub-bitstream.

The encoding and decoding scheme is illustrated in Fig. 2. The encoding part consists of three steps. First, the texture and geometry atlases are generated using the Test Model of Immersive Video (TMIV) encoder [17]. Second, each atlas is then compressed using the VVC Test Model (VTM) [18]. Finally, each pair of texture and geometry atlas is merged into a single bitstream using the subpicture merge tool [19], which is a part of the VTM package.

Rendering a viewport from the coded MIV bitstream involves first decoding the packed atlases, extracting only the texture and geometry subpictures by splitting the packed decoded atlases, and finally rendering the viewport using the TMIV decoder.

A. Encoding

The texture and geometry atlases are generated using TMIV [17]. The size of a subpicture must be an integer multiple of min CU size, as specified by the VVC standard. Therefore, before VTM encoding, each atlas is padded along columns and rows to satisfy this constraint. Any rectangular empty space that remains after packing of texture and geometry atlases is completed by generating a filler sequence and encoding it to create a filler bitstream. The filler sequence consists of YCbCr images with some constant value in the Y, Cb, and Cr planes. The exact value in the filler image does not matter because it is neither decoded nor used for rendering.

B. Subpicture merging

VTM [18] encoder includes sample configurations that enable the usage of the subpicture tool. It is possible to merge multiple independent bitstreams into one, where each picture (frame) within the separate bitstreams becomes a subpicture in the merged bitstream.

In the merging step, the coded texture, geometry and filler bitstreams are merged using a subpicture bitstream merging tool provided by VTM. A frame of the resulting packed atlas, after merging, is shown in Fig. 1.

C. Bitstream formatting

After merging the three bitstreams, an MIV is presented with a V3C packed video component which is multiplexed to MIV bitstream. In order to allow a client to correctly interpret the decoded data, an additional signalling is included in the VPS. The extra signalling describes the type of each region, its position and orientation in the packed frame. Additionally, a packed independent SEI message can be included in the MIV bitstream. The SEI message provides the mapping of regions in the packed video atlas to VVC subpicture identifiers, and it facilitates partial access of data in the MIV bitstream.

D. Decoding

Arbitrary views from within the viewing volume can be generated by doing the following: (1) decode the merged bitstream using VTM decoder; (2) extract the texture and geometry atlases from the decoded packed atlas using information from the VPS; and (3) decode the remaining parts of the MIV bitstream (i.e. V3C atlas components) using the TMIV decoder and render the required viewport.

VII. EXPERIMENTAL EVALUATION

MIV common test conditions document [3] defines evaluation methods as well as test content. For the purpose of this paper, only a subset of the sequences was evaluated; namely ClassroomVideo, Frog, and Chess, which are shown in Fig. 3 and their characteristics summarised in Table I.

The Computer Generated (CG) sequences contain near-perfect depth maps, whereas Natural Content (NC) sequences contain estimated depth maps. Some sequences consist of ERP views and others were captured with perspective cameras. Moreover, the resolution varies from full High Definition (HD) to UHD.

The experiments were carried out under A17 configuration, meaning only 17 frames were used. The atlases are generated with TMIV 7.0 and are encoded with VTM 11.0 using

| Sequence       | Type | Resolution   | Frame rate | Views |
|----------------|------|--------------|------------|-------|
| ClassroomVideo | E    | 4096 × 2048  | 30         | 15    |
| Frog           | P    | 1920 × 1080  | 30         | 13    |
| Chess E CG     | C    | 2048 × 2048  | 30         | 10    |
random-access configuration along the parameters displayed in Table II. Each atlas is encoded using two sets of QPs, QP1 to QP4 (high bitrate) and QP2 to QP5 (low bitrate). Moreover, all experiments ran on cores Intel Xeon E5-2695 v2 @ 2.40GHz.

The texture QPs are sequence dependent, and they target 5 to 50 Megabits per second (Mbps) bitrate range as defined in Table III. Each texture QP \( q \) is paired with a geometry QP \( q' \) that is calculated, as specified in the Common Test Conditions (CTC), as follows:

\[
q' = \text{round}(\max(1, -14.2 + 0.8 \cdot q))
\]  

(1)

The quality of the reconstructed source-views is evaluated by computing objective quality metrics. Specifically, the metrics used are the Peak Signal-to-Noise Ratio (PSNR), the Weighted-to-Spherically-uniform PSNR (WS-PSNR) [20], the Immersive Video PSNR (IV-PSNR) [21], and the Video Multimethod Assessment Fusion (VMAF) [22]. Furthermore, the Bjøntegaard Delta rate (BD-rate) [23] is computed for each of these metrics.

The BD-rate results are summarised in Table IV. The proposed approach incurs in negligible coding losses, up to 0.4%, due to the overhead associated to the filler video coded data required to create the merged bitstream (IRAP subpictures use in average 236 bytes and inter-coded subpictures use in average 14 bytes). The results are slightly higher for Frog as the overhead includes the filler video and the texture and geometry atlases are padded along the width and height. Nevertheless, the quality of reconstructed source-views is almost identical between the anchor and the proposed approach.

The complexity of the approach is based on the runtime ratios (Table V). There are three main outcomes. First, the TMIV encoding and the TMIV decoding have similar complexities as these two operations are changeless. Second, the complexity of the padding operation, encoding the filler with VTM and the merging operation are almost negligible. Finally, the more demanding operations are the decoding of the merged bitstreams with VTM and extracting afterwards the texture and geometry atlases. Note that these two last operations can be improved by extracting and decoding only the required subpictures.

The overall pixel rate of the merged bitstream can be reduced by changing the orientation of the atlases, in order to reduce the dimensions of the filler component.

Since it is possible to maintain the quality of reconstructed source-views, coding texture and geometry atlases as subpictures within the same bitstream is a feasible approach.
This paper used the subpicture tool of VVC to code 6DoF immersive video. The independently extractable and decodable property of subpictures provides additional flexibility in the coding of 6DoF immersive videos, some of which were elaborated upon. A specific case, where the texture and geometry atlases generated by MIV are coded as subpictures within the same atlas, was selected for experimentation. The results showed that while there is a small (0.1% to 0.4%) BD-rate overhead incurred, the number of decoder instantiations required is reduced by half. The evaluated approach also provides the ability to independently encode, extract, and decode parts of the coded bitstream, thus improving parallelism.

While this paper focused on one specific case, it is evident that there may be many other cases, specifically for coding large dynamic 6DoF volumetric videos, where subpictures could be found useful.

VIII. CONCLUSION

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