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Delivering Object-Based Immersive Video Experiences

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Abstract

Immersive video enables interactive natural consumption of visual content by empowering a user to navigate through six degrees of freedom, with motion parallax and wide-angle rotation. Supporting immersive experiences requires content captured by multiple cameras and efficient video coding to meet bandwidth and decoder complexity constraints, while delivering high quality video to end users. The Moving Picture Experts Group (MPEG) is developing an immersive video (MIV) standard to data access and delivery of such content. One of MIV operating modes is an object-based immersive video coding which enables innovative use cases where the streaming bandwidth can be better allocated to objects of interest and users can personalize the rendered streamed content. In this paper, we describe a software implementation of the object-based solution on top of the MPEG Test Model for Immersive Video (TMIV). We demonstrate how encoding foreground objects can lead to a significant saving in pixel rate and bitrate while still delivering better subjective and objective results compared to the generic MIV operating mode without the object-based solution.

Introduction

Advancements in digital media technology are enabling worldwide adoption of immersive media by bringing innovative six Degrees of Freedom (6DoF) visual experiences of immersive media formats, such as multi-view video, point-cloud video and volumetric video, to mass-consumer market. By enabling 6DoF with motion parallax and wide-angle rotation capabilities, an immersive media platform shown in Fig. 1 allows viewers to navigate the content in a more natural, personalized and interactive way.

A complete real-time immersive media platform includes everything from the capturing of immersive content to the production, processing, and delivery of immersive visual experiences and services. For a real-time immersive media platform, it is difficult to move large amounts of captured media data along a media processing pipeline with minimal latency, compute the immersive media data efficiently with resource constraints, and deliver the best possible quality of media content over limited network bandwidth. Given those challenges, such immersive experiences have previously been limited to virtual videos, pre-synthesized at the capture side, where the content creator determines the navigation path, renders ordinary 2D video for the navigation path, and distributes content using legacy video distribution methods.

The coded representation of immersive media being developed by the Moving Picture Expert Group (MPEG), is part of the MPEG-I [1] project, which is an industry effort to develop a suite of standards to support immersive media access and delivery. By leveraging the state-of-art high efficiency video compression technologies, e.g., HEVC, MPEG Immersive Video (MIV) [2], one of the MPEG-I standards, is promising to deliver a standard-based coding solution without compromising the interactivity and 6DoF capabilities of immersive media content. One of MIV operating modes is the object-based immersive video coding which enables novel use cases for objects within the immersive content at the encoding and decoding stages.

In this paper, we first show an example immersive video sequence with the generated object maps. Then we discuss the novel use cases enabled by our object-based coding scheme. Afterwards we explain the design of object-based MPEG immersive video coding and how it is implemented in the Test Model for Immersive Video (TMIV) [3], the reference software of MIV. The quality improvement as well as the bandwidth saving, and the performance gain of the object-based solution are evaluated.

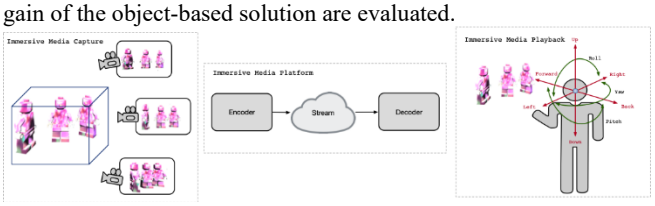


Figure 1. Immersive media capture, platform, and playback stages delivering 6DoF experience

Immersive Video Content Sample

One of the synthetic content sequences, called Museum [4], used during the MIV development process has been utilized here. We first describe the sequence and its object maps that we have generated from it to showcase the object-based solution.

Museum Content

The dataset represents a time-sequence of 300 frames, where each frame contains 24 views rendered from 24 virtual cameras each directed normal outward to a sphere, see figure 2-left. Each view is made up of a 2048x2048 texture image and a corresponding16-bit depth image (see Figure 2-right) stored as equirectangular projections with a 180-degree vertical and horizontal field of view. Camera position, orientation, and projection information are provided for all 24 views.

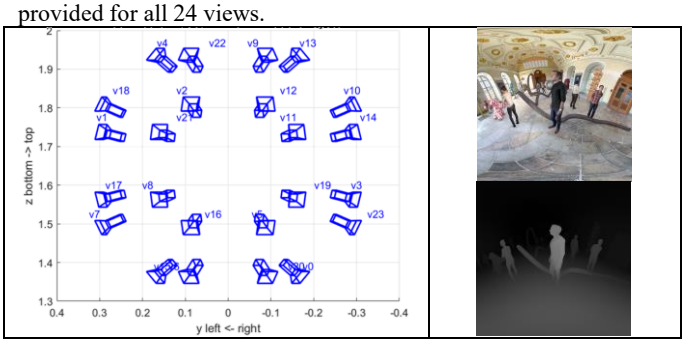


Figure 2. Capturing camera system composed of 24 cameras (left) along with the texture and depth components of one of the views at a given frame

Object Maps

Our object-based coding solution requires input information which indicates which object each pixel within a view per frame belongs to. This can be provided in a form of supplemental object maps associated with the content. For the Museum sequence, the object maps feature 25 different objects indexed as illustrated in Fig. 3. Note that for this content, ObjectIDs [0, 5] are reserved for the background objects while ObjectIDs [6, 24] are reserved for all other foreground objects in the scene. The generation of these object maps is further explained in appendix A.1.

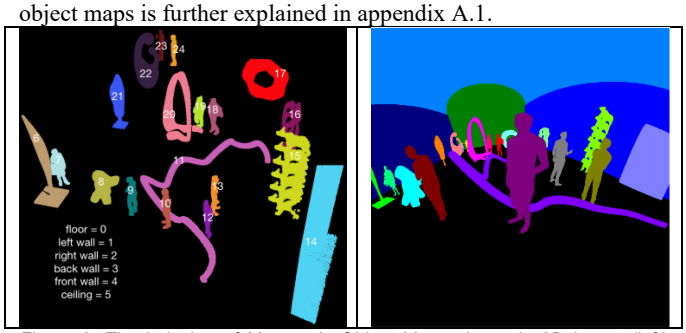


Figure 3. The indexing of Museum's Object Maps shown in 3D layout (left) and color-indexed object map of v5 – frame 100 (right).

Object-Based Immersive Applications

The object-based coded representation of immersive media enables many novel use cases for volumetric video coding and rendering. In addition, it helps addressing several MPEG requirements for immersive media access and delivery [5] including the manipulation of decoded objects at higher level without having access to the actual pixel information.

Priority Objects Rendering

Object-based coded representation of immersive media speeds up processing of content at the decoding side to meet real-time requirements. Each object in the bitstream can be signaled for its priority over the rest of the objects. When such object priority information is available at the decoder side, the renderer can choose to process the high priority objects only while dropping low priority objects to meet latency or computing constraints.

Objects Filtering

Since each object is coded individually, viewers may choose to view only the objects of interests while not displaying the other objects. Object-based coded representation not only allows such kind of personalized viewing on the decoder side but also allows the encoder to pack only objects of interest in the bitstream in the event of limited network bandwidth or supporting less capable client devices.

Background Rendering

In object-based code representation, background is considered to be a special object that can be rendered by itself independent of other objects. The background object can be synthesized from virtual / pre-rendered content. For example, the venue of a sports game can be synthesized as a 3D model ahead of a live game and used for rendering as the background in a scene augmented with objects (players, balls, etc.) captured from the live game.

Object-Based Scalability

Traditional adaptive streaming technique alters the quality of entire video stream in order to fit to different network conditions. In object-based coded representation, encoder may use contextual information available to it to decide the relative importance of different objects and provide object-based scalability for adaptive streaming. For example, unimportant objects, e.g., objects too far away from a viewport, can be dropped entirely or compressed at lower visual quality. The quality for objects that are important to the viewers does not degrade even at lower network bandwidth.

Objects of Interest

Object-based coded representation also allows highly personalized content because each object can be compressed in different visual quality. If one is interested in a specific object, one can select the stream with the object-of-interest encoded in higher visual quality.

MPEG Immersive Video Coding

The immersive video format that is input to a MIV encoder is a multiplicity of synchronized view videos captured by real and/or virtual cameras that can be arranged in a variety of configurations, including outward-facing, inward-facing, or a planar camera array. The content can be synthetic (i.e. computer generated) or natural (i.e. real-world) and in 360 degree (e.g. equirectangular) or perspective projection format. Each view is composed of two components; a texture content (e.g. RGB / YUV channels) and its associated depth map (whether captured or estimated).

The MIV standard [2] is based on the Visual Volumetric Video-based Coding (V3C) specification and aims at exploiting redundancy between the views and leveraging state-of-art video codecs to deliver the best quality at minimal bandwidth and with a minimum requirement of decoder complexity. The MIV standard defines the format of the compressed bitstream and the normative decoding process to deliver the 6DoF experience while TMIV [3], its reference software, provides an exemplary full implementation of the encoder and decoder stages. A brief description of the TMIV software is given here to establish the technical background for the object-based solution described in a later section.

The immersive media content streamed in MIV can be navigated with 6 DoF by a wide range of consumer devices which contain video decoding hardware and a GPU, such as computers with face tracking camera, smartphones/tablets with inertial sensors, head-mounted displays, volumetric and multi-view displays.

TMIV Encoder

The TMIV encoder takes as inputs texture and depth videos for multiple synchronized source views, each at a particular position and orientation. The input views are processed using reprojection between views to remove redundant regions, in order to reduce the bitrate and pixel rate needed to represent the whole content.

The TMIV encoder identifies a few of the views as basic views, each of which is fully encoded within a single patch. The additional views are then projected against the basic ones (and previously pruned ones) to extract the non-redundant information in a form of rectangular patches and pack them into atlases (composed of texture and depth components) during the atlas construction process. Occupancy maps are also generated to indicate the active pixels (for the non-redundant regions) per patch and helps resolving overlapped patches later at the decoding stage. The occupancy maps are embedded within the lower range of the depth component of the atlases. The atlases are finally encoded using the existing HEVC video codec. The associated view parameters list (illustrating how views are placed and oriented in the coordinate space) and the atlas data (indicating how patches are mapped between the atlases and the views) are carried as metadata

within the bitstream. The encoding process of a simplified TMIV software is summarized in Fig. 4 while example atlases are shown in Fig. 7.

The TMIV encoder attempts to optimize bitrate, to reduce the network bandwidth requirements, and to optimize pixel rate, which directly impact decoder complexity requirements. Pixel rate is calculated as the resolution of the combined atlases multiplied by the frame rate.

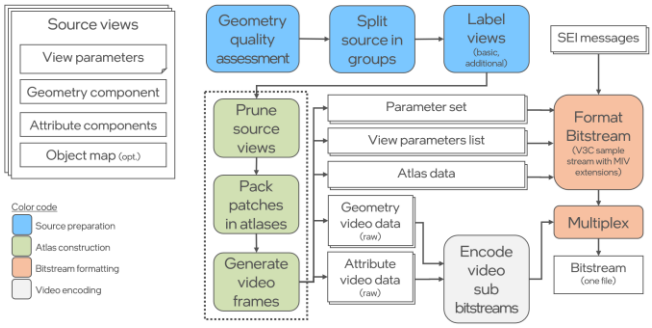


Figure 4. Flow diagram of a simplified TMIV encoder

TMIV Decoder

At the decoding stage, video decoding is applied to retrieve the atlases, the metadata is parsed, and the occupancy maps and block to patch maps (indicating patchIDs of each pixel in the atlas) are recovered. The renderer then within the exemplary TMIV decoder outputs a perspective viewport, selected based upon a viewer's position and orientation, generated from the decoded atlases and metadata of the immersive decoder. The TMIV rendering process is illustrated in Fig. 5 which includes a patch culling step to exclude all patches that do not contribute to the viewport, a geometry process to retrieve the geometry at full resolution and find the metric depth, the reconstruction of pruned views, the unprojection and reprojection to the target viewport, the merging and inpainting steps. The complexity of the TMIV decoding process is largely driven by the pixel rate. Note that the MIV standard [2] itself does not specify the reference renderer but supplies it with the required metadata and decoded content.

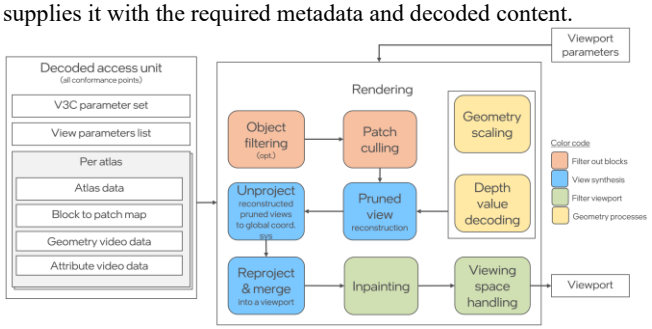


Figure 5. Flow diagram of a simplified TMIV renderer

Object-Based Implementation in TMIV

As the encoding and decoding stages of the TMIV software have been introduced, we explain here the modifications added on top of the software to bring the object-based capabilities to it. Note that the TMIV software including the object-based solution is accessible publicly on the Gitlab server at https://gitlab.com/mpeg-i-visual/tmiv/.

Object-Based Encoder

The modified TMIV encoder features an object-based atlas constructor which is illustrated in Fig. 6. All other blocks are left unmodified as in the original TMIV encoder. Note that in the object-based solution, object maps for all views and frames are made available as an input as well in addition to the texture content and depth maps. Also, the basic views here are just used for pruning and packing but not being streamed since each patch shall carry only pixels that belong to a specific object. Some components of the atlas constructor operate on frame level while others on intra-period level (i.e. random-access period).

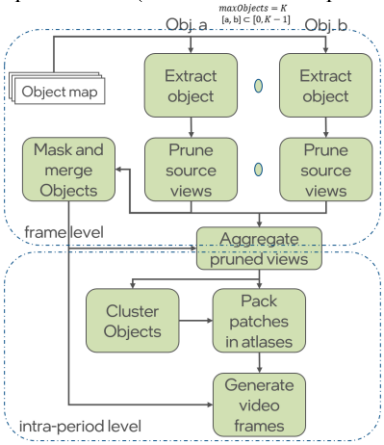


Figure 6. Flow diagram of an object-based atlas constructor inside TMIV encoder

Frame Level Operations

The object-based atlas constructor takes as an input the texture, depth, and object maps of the frame being processed in addition to what views being labeled as basics along with their camera parameters. A loop is established over the objects selected for the encoding (whether preset by a user or decided based on an encoding metric) where in each iteration the related object layers are extracted from the frame's views (texture and depth) and passed to the pruner which finds the nonredundant parts and returns the related binary masks. Note that the looping over the pruner can be parallelized over various objects since there is no dependency and to maintain reasonable encoding time.

The pixels of the basic views' masks by default (i.e. in the original atlas constructor) are turned on (i.e. set entirely to max grey level) denoting that the entire basic views are streamed in whole patches. However, for the object-based implementation no patch can have pixels belong to more than one object at a time. Thus, the basic masks are updated in the object masker based on the object maps such that pixels are turned on only for pixels belong to the extracted object. The other pruning masks are refined as well to accurately represent the object. Then object masks are formed such that the related objectID is assigned to all "on" pixels within the refined masks (across all views) for the frame being processed. The object masks are merged with those in the previous iteration, this way objectID can be tracked and patches can be tagged with the right objectID label at a later stage. The object layers resulted from the object separator stage are also merged together and pushed into a buffer so they can be used in the atlas generation stage. The aggregator then aggregates the pruning binary masks and the merged multi-level object masks to account for motion across frames within an intra-period.

Inter-Period Level Operations

After processing all frames within an intra-period (i.e. random-access period), the aggregator terminates the accumulation of the masks and passes them to the patch packer. The aggregated object masks are then used to filter out the binary masks, so clustering is applied per object and the resulted clusters are tagged with the related objectID and queued together. After clustering over all objects, the clusters are ordered based on how many active pixels they include (unless they belong to the basic views). Patches are then formed from the clusters and packed into the atlases. Note that each patch carries the same objectID of the cluster that initiated it. Finally, an atlas generator is deployed to write the texture and depth content of the patches. The content of a given patch is extracted from the associated object views passed by the object masker and merger block.

Object-Based Decoder

The TMIV renderer has been modified to support the object-based filtering and rendering operations, although block-wise it remains as illustrated in Fig. 5 (but now the object filtering block will be in used). The user can pick a desired set of objects to be rendered, and the block to patch map per atlas is updated such that the patchIDs of patches that carry objectIDs of excluded objects are set to unoccupied. This way the renderer ignores them when synthesizing the desired viewport. Since pixels of filtered out objects might be still occupying pixels in the rendered viewport, the inpainter assumes missing info and try to fill them causing stretched artifacts. Thus, in this implementation we are bypassing the inpainter for inactive pixels outside the rendered objects and simply fill them by a neutral color.

Object-Based Video Coding Study

A Common Test Conditions (CTC) [6] procedure has been established by the MIV group to evaluate improvements and solutions proposed for immersive video coding. We follow the CTC guidelines and report below the objective and subjective results of object-based coding (encoding foreground objects only) compared to the MIV anchor (i.e. encoding full-content but using the ordinary MIV operation mode). For the object-based coding, we only select the foreground objects to be encoded and reduce the number of outputted atlases to 1. The study is conducted using TMIV software-version 7.2.

In terms of encoded atlases, the MIV anchors encoding full content requires 2 atlases (of texture size 2048×4352 and 2048×1824) however the object-based solution requires only 1 atlas (of texture size 2048×2272) for encoding foreground objects resulting in ~65% saving in pixel rate. The atlases of both approaches are shown in Fig. 7. Note how in the object-based solution, patches packed in the atlas only include content of a single object per each. Also, there is no basic view being streamed yet the patches coming from the basic views are prioritized during the packing process.

The atlases are HEVC video encoded following the CTC guidelines and decoded accordingly. The block to patch maps are filtered to keep foreground objects as well. The rendered views have no background content hence the objective metrics are computed with background pixels being masked out to get an unbiased objective comparison. In other words, object maps are used to mask both the reference source views and the reconstructed ones such that background pixels are substituted with neutral grey. The masking procedure is also applied to MIV anchor's rendered views so only the foreground object pixels are included, for a fair comparison with the object-based coding results.

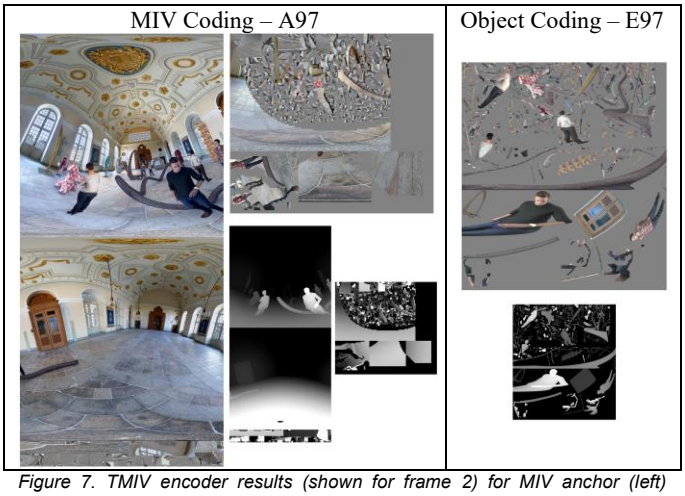
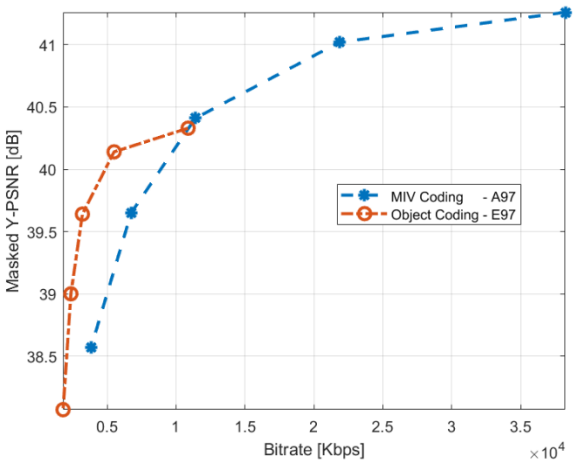


Figure 7. TMIV encoder results (shown for frame 2) for MIV anchor (left) including 2 atlases and encoding full-content and for object-based coding results (right) including 1 atlas encoding only foreground objects.

Three objective metrics are used for the evaluation according to the CTC: the weighted-to-spherically uniform PSNR [7], the Video Multimethod Assessment Fusion (VMAF) [8], and the Immersive Video PSNR (IV-PSNR) [9]. The objective results of the delivered quality vs bitrate for various quantization points (QPs) are illustrated numerically in table 1 and as curves in Fig. 8. Note the significant saving in bit distortion rates across various metrics (~46% in PSNR, ~57% in VMAF, and ~56% in IV-PSNR) when excluding the background content. Also, in terms of the processing time the rendering speed of the foreground objects here is nearly double the speed when rendering the full content.

Table 1. Objective results (in terms of low & high bit distortion rates of various metrics) showing the gain when foreground object coding is used compared to the MIV anchor.

Sequence		High-BR BD rate Y-PSNR	Low-BR BD rate Y-PSNR	High-BR BD rate VMAF	Low-BR BD rate VMAF	High-BR BD rate IV-PSNR	Low-BR BD rate IV-PSNR
Museum	SB	-42.4%	-49.3%	-58.5%	-56.2%	-56.4%	-55.8%



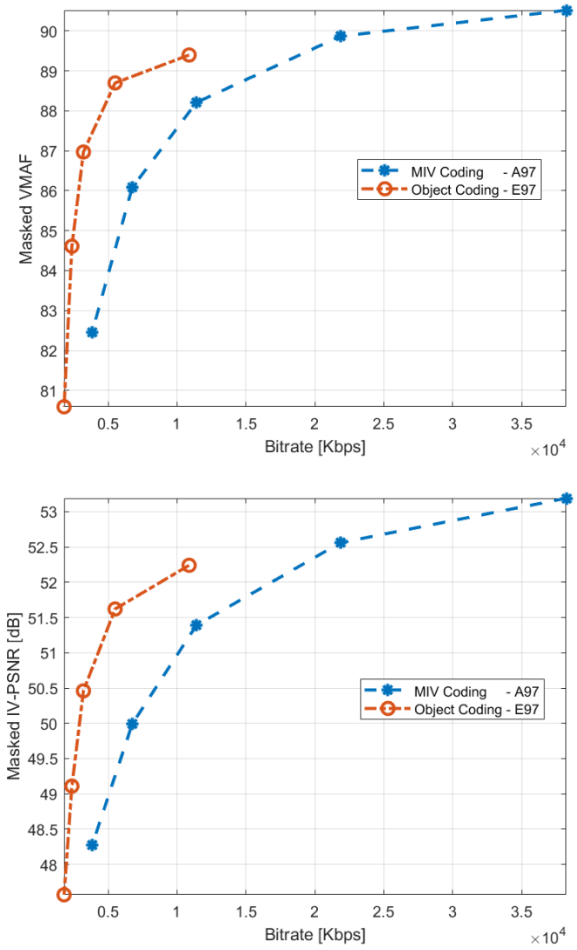


Figure 8. The rate-distortion curves of object-based solution (dot dashed red curves) compared to MIV anchor (dashed blue curves) using masked Y-PSNR (luma channel only) (top), masked VMAF (middle), and masked IV-PSNR (bottom).

Figure 9 shows subjective comparison between MIV anchors & object-based coding results at 3rd frame of v5 [6] at nearly matched bitrate. We can see better subjective results (e.g. more details on faces of the actors, fine textures on the snake-shaped sculpture) in the object-based coding case. There are two key reasons why the object-based coding produces better subjective results. The first is that by reducing the amount of content to be coded by excluding the background areas, the HEVC QP can be reduced while meeting the same bitrate. In addition, the artifacts created by HEVC encoding the depth atlas can be reduced by avoiding having significant differences in depth values within the same patch, e.g. foreground and background depth values.

The improvements in subjective quality prove the main motivation of the object-based solution where streaming bandwidth can be more efficiently geared to deliver the objects of interest in a better quality rather than sacrificing the whole content to fit in case of a limited bandwidth.

Figure 9. Subjective results of object-based solution compared to MIV anchors showing a zoomed version of v5-frame 2 of MIV anchor-QP5 (top) and object-based coding -QP3 (below). Note the subjective results are shown for different QPs but with nearly matched bitrate.

Conclusion

An object-based coding solution is introduced into the MPEG Immersive Video (MIV) to enable innovative immersive experiences including efficient bandwidth utilization for encoded objects of interest and personalized rendering of selected objects on synthesized background. A software implementation is available in the Test Model for MPEG Immersive Video (TMIV) for both the encoding and decoding stages. The solution produces patches that include a content for a single object per patch, allowing each patch to be associated with an objectID. When excluding the background objects from the encoded stream of one of the MIV sequences (i.e. the Museum sequence), the coding results show a ~65% saving in pixel rate, ~50% gain in bit-distortion rate, and rendering at nearly double speed as opposed to encoding and rendering the full content. Reduction of pixel rate enables support for immersive video playback on a wider range of decoder devices. We also report significant improvement in the subjective quality of object-based solution compared to MIV anchors which serves as a proof that the streaming bandwidth budget can be better geared toward delivering the objects of interest in a better quality as oppose to a global reduction in quality when streaming the whole content within a limited bandwidth.

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Appendix

Object Maps Generation

Given the intrinsic and extrinsic camera parameters we can compute the 3D location associated with each pixel in the texture of a known depth value. Figure 10 - left shows the point-cloud constructed from its associated depth and texture images. The shadow-like holes in the point-cloud result from the large number surfaces that are occluded from the single camera's viewpoint. A more complete point-cloud can be created for each frame by transforming all the point-clouds from every camera into a common coordinate system. We leverage point-cloud clustering techniques to segment each frame into its constituent objects as describe here.

Since the data is effectively noiseless (i.e. synthetic), we can accurately isolate the various objects in the scene. For a given frame we reconstruct a point cloud, Fig. 10-left, using the corresponding ground-truth depth maps and the exact camera parameters. If we remove the points representing the floor object, then the segmentation problem of various objects within the frame is reduced to a 3D *connected components* problem *(i.e.; point-cloud clustering*).

Background Removal

The floor object can be removed by numerically computing a best fitting plane for the floor geometry via the method of least squares. We can then cull all points that lie close to the plane, see Fig. 10-center. By repeating this procedure for the remaining walls and ceiling we remove the remaining background points, see Fig. 10-right. Note that each background object is assigned a unique objectID which are in the range [0, 5] for the Museum sequence, illustrated in Fig. 3-left.

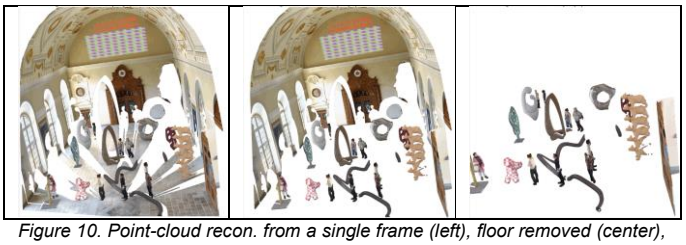

Figure 10. Point-cloud recon. from a single frame (left), floor removed (center), background removed (right).

Per-frame Clustering

After assigning the background pixels their associated objectID, we investigate the labeling for other objects. An *object mask* (to contain the resulting cluster labels for each pixel in the frame) is initialized and background pixels are labeled. Then an unlabeled pixel is selected as a seed value, and the mask is *flood-filled* (i.e. over the connected neighboring pixels) and assigned the next available object label. The flood-fill uses a threshold on the distance between the reconstructed 3D points associated with each pixel as the criterion for propagating the label value. This process is repeated until all pixels are assigned a label. Note that the mask not only stores the object labels but also controls the boundaries of the flood-fill.

Consistent Labeling

The remaining problem is to find a consistent labeling across views and frames. Also, some objects will be divided into multiple pieces (e.g. the metallic snake that goes through various objects) which we want to merge and assign a single label as shown in Fig. 11. To accomplish this, we build a complete point-cloud for each frame using all 24 views and perform a full 3D clustering to define a *canonical label* for each object. Each frame's cluster labels are then remapped to their canonical value by finding the closest cluster in the canonical cluster set. Furthermore, since the objects do not move much within the sequence and are reasonably separated, we only compute the canonical clusters for the first frame and carry-out the labeling results across all frames as opposed to laboriously creating point-cloud clusters for all 300 frames and unifying their label values.

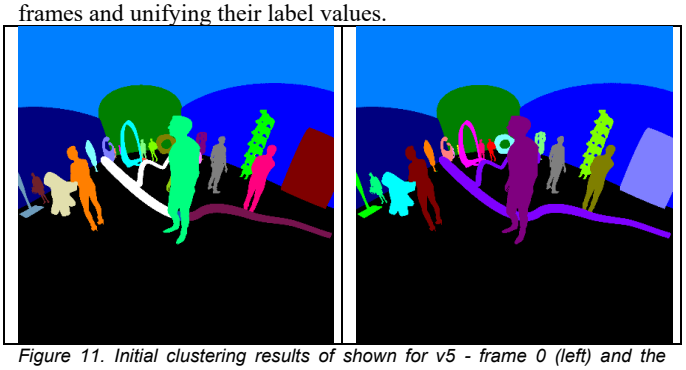

Figure 11. Initial clustering results of shown for v5 - frame 0 (left) and the refined consistent labeled clusters (right), note that piecemeal clusters are merged to single objects. Note how the snake metal object (behind the person at the center) was broken to 4 pieces initially but combined into one object label eventually.

Biography

Basel Salahieh is immersive media algorithms and standards architect at Intel (CA, USA) responsible for delivering immersive experiences on intel devices, holding a Ph.D. degree in electrical and computer engineering and M.S. in optical science from the University of Arizona (AZ, USA), M.S.

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Jill Boyce is Intel Fellow and Chief Media Architect at Intel, responsible for defining media hardware architectures for Intel's video hardware designs. She represents Intel at the Joint Video Exploration Team (JVET) of ITU-T SG16 and ISO/IEC MPEG. She serves as Associate Rapporteur of ITU-T VCEG, and is an editor of the MIV specification. She is an IEEE Fellow. She received a B.S. in Electrical Engineering from the University of Kansas in 1988 and an M.S.E. in Electrical Engineering from Princeton University in 1990. She was formerly Director of Algorithms at Vidyo, Inc. where she led video and audio coding and processing algorithm development. She was formerly VP of Research and Innovation Princeton for Technicolor, formerly Thomson. She was formerly with Lucent Technologies Bell Labs, AT&T Labs, and Hitachi America. She was Associate Editor from 2006 to 2010 of IEEE Transactions on Circuits and Systems for Video Technology.

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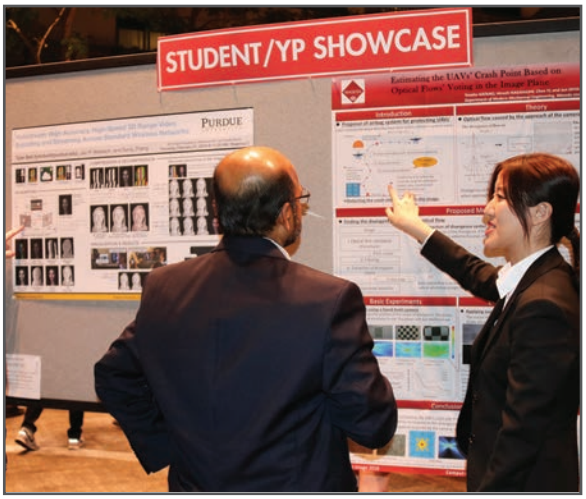

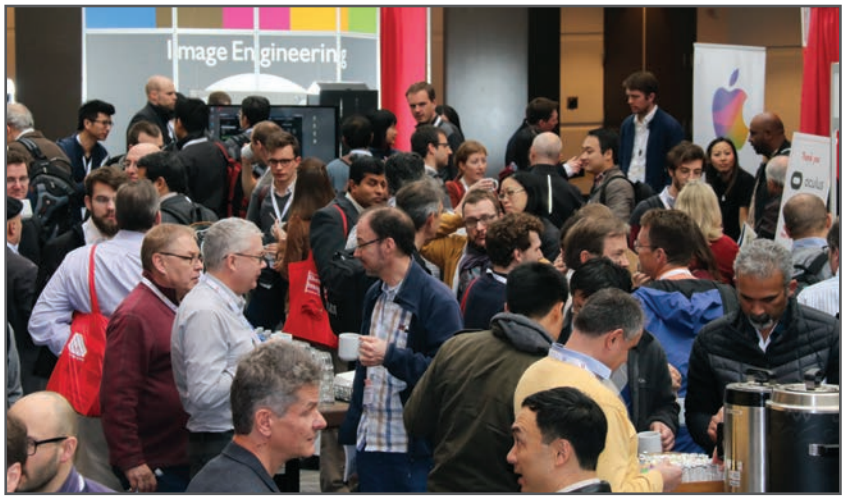

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