Point Cloud Rendering after Coding: Impacts on Subjective and Objective Quality

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Abstract—Recently, point clouds have shown to be a promising way to represent 3D visual data for a wide range of immersive applications, from augmented reality to autonomous cars. Emerging imaging sensors have made easier to perform richer and denser point cloud acquisition, notably with millions of points, thus raising the need for efficient point cloud coding solutions. In such scenario, it is important to evaluate the impact and performance of several processing steps in a point cloud communication system, notably the quality degradations associated to point cloud coding solutions. Moreover, since point clouds are not directly visualized but rather processed with a rendering algorithm before shown on any display, the perceived quality of point cloud data highly depends on the rendering solution. In this context, the main objective of this paper is to study the impact of several coding and rendering solutions on the perceived user quality and in the performance of available objective quality assessment metrics. Another contribution regards the assessment of recent MPEG point cloud coding solutions for several popular rendering methods which was never presented before. The conclusions regard the visibility of three types of coding artifacts for the three considered rendering approaches as well as the strengths and weaknesses of objective quality metrics when point clouds are rendered after coding.

Index Terms—point cloud coding, quality assessment, subjective quality assessment, rendering

I. INTRODUCTION

Nowadays, emerging 3D visual representations allowing more immersive experiences compared to the classical 2D images or videos are attracting much interest. In fact, a new wave of multimedia applications are now possible, from geographical information systems, and virtual and augmented reality to cultural heritage and free viewpoint broadcasting, motivated by the recent advances in 3D acquisition systems [1]. In this context, point clouds are becoming an important 3D visual representation format of the real world due to the availability of several acquisition devices (from range sensors to multi-camera arrays) as well as efficient coding solutions and rendering techniques. A point cloud (PC) is a set of 3D points represented by their 3D coordinates and associated attributes, such as color, normals and reflectance. PCs can be classified with respect to their temporal evolution. While static PCs correspond to a single time instant, dynamic PCs correspond to a PC evolving along time, thus corresponding to a sequence of static PC frames. Also, progressive PCs correspond to large-scale PCs that are not consumed all at once and thus are made from complementary parts of a visual scene; these parts are static PCs that differ both spatially and/or temporally (often used in autonomous driving).

To represent the visual scene with high fidelity, a PC can have several millions or even billions of points, which results in a large amount of data that needs to be efficiently stored and transmitted. Thus, coding technologies are essential to deal with the huge amount of data that PC acquisition devices can generate. The coding solutions already available [2]-[5] can be lossy or lossless and aim to reduce the PC representation bitrate while keeping the data fidelity/quality as high as possible. Following the demands by the industry, both JPEG and MPEG standardization bodies recognized that the PC format can address future immersive multimedia applications and have initiated projects in the area of PC coding [6][7][8]. In January 2017, MPEG has issued a Call for Proposals on Point Cloud Compression (PCC) [9], targeting the efficient representation of static objects and scenes, as well as dynamic objects and real-time environments. After this call, two PC coding solutions have been developed, notably the so-called Geometry-based Point Cloud Compression (G-PCC) standard [10], for static and progressive acquired content and Video-based Point Cloud Compression (V-PCC) [11] standard, for dynamic content.

Naturally, PC quality assessment is fundamental to evaluate the performance of the several processing steps in PC-based applications, notably denoising, coding and rendering. Moreover, subjective quality assessment procedures and objective quality assessment metrics that can accurately evaluate the perceived quality, notably when PC data is compressed, are much needed. Both are critical to improve the final Quality of Experience (QoE) offered to the end-users, not only to monitor the quality of the experiences but also to allow the design and optimization of novel PC coding techniques.

PCs can be visualized on a variety of devices, such as 2D displays, head mounted displays (HMDs), augmented reality devices and even on stereoscopic or multi-stereoscopic displays. However, independently of the type of display, PCs cannot be directly visualized and require a rendering technique to create the data that may be visualized; this can be seen as a post-processing step after decoding. Nowadays, there are multiple PC rendering approaches [12] [13] that may significantly influence the perceived PC quality in different ways. While there are several subjective and objective quality evaluation studies available in the literature, they do not use the same type of coding and rendering solutions as well as test conditions and thus, rather often, reach different conclusions. Therefore, it is critical to study the impact of different rendering approaches on the subjective and objective PC quality.

On the other hand, many relevant past works on subjective and objective quality assessment [14]-[20] rely on simple coding solutions such as octree pruning, which are inefficient and produce a rather distinctive type of artifacts. However, more sophisticated and also more efficient lossy PC coding solutions...
are now available, which produce decoded PCs with very different characteristics and artifacts. As an example, some PC codecs significantly increase the number of decoded points to hide coding artifacts, thus achieving a better perceived quality. This makes the subjective and objective quality assessment of PCs more complex, especially when more efficient coding and rendering solutions are considered.

While PCs have commonly two major components, geometry and texture, this paper focus on the quality impacts of degradations on the geometry component of the PC representation. Geometric artifacts are very important for the final perceived quality since this type of degradations may reduce the realism of the decoded geometry, e.g. due to the appearance of holes and noisy surfaces, consequently leading to poorer user immersion. Fig. 1 shows an example of geometric artifacts, in this case associated to the MPEG G-PCC codec, which clearly results in a rather low perceived quality.

Fig. 1. Arco Valentino PC: left) original PC; and right) MPEG G-PCC decoded PC. Original texture used for recoloring.

The objective of this paper is to study in a subjective way, the impact of the different artifacts produced by state-of-the-art PC codecs for different types of rendering and assess objective PC quality metrics in several scenarios. This is the first time that the rendering $R$ and coding $C$ processes, which play a major role on the final perceived quality, are jointly evaluated in this case for static point clouds. In this context, the main contributions are:

- **PC rendering after coding – subjective quality assessment:** Study of the subjective quality impact of multiple $(R, C)$ combinations for relevant, lossy PC coding and rendering solutions. Moreover, the visibility of the distortions associated to each codec under different rendering scenarios will be analyzed. This first contribution is critical for the design of a suitable PC subjective assessment methodology, where a rendering solution must be chosen.

- **PC rendering after coding – objective metrics assessment:** Evaluation of the performance of available PC objective quality metrics for multiple $(R, C)$ combinations, i.e. for different types of rendering and coding artifacts. This should allow understanding the strengths and weaknesses of available objective quality metrics as well as their scope of validity, i.e. for which conditions these metrics represent well enough the human perceived quality. This second contribution is critical for the design of more reliable PC objective quality metrics, notably for the evaluation of new PC coding solutions as well as associated techniques.

This paper is organized as follows. Section II reviews the related work while Section III describes three key PC coding and rendering solutions, which are used for the following experiments. Section IV describes the subjective evaluation study along with some key conclusions. Section V aims to evaluate the most relevant PC objective quality metrics. Finally, Section VI concludes the paper and proposes some future work.

II. RELATED WORK

In the literature, there are several subjective and objective PC quality assessment methods and studies available. In [21], Zhang et al. designed a subjective test for colored PCs for different levels of degradation of both geometry and color. The quality degradations have been introduced by down-sampling the geometry and independently adding (synthetic) uniform noise for both color and geometry. The main conclusion was that human perception is more tolerant to color noise compared to geometry noise in PCs.

In [22], Mekuria et al. conducted the subjective evaluation of a PC codec based on geometry octree pruning and JPEG based attributes coding. The subjective evaluation was performed in a mixed reality system, combining coded PC data (acquired) and computer graphics generated 3D content. In the subjective test, the users could interact with the content by navigating a visual scene with an avatar. The system performance was globally assessed with a questionnaire addressing eight different quality aspects, notably realism, immersion and color quality. Two objective quality metrics (mean squared error based) were introduced to assess both the geometry and color qualities. However, the correlation between objective metrics and subjective results was not assessed.

In [23], Javaheri et al. performed the subjective and objective quality assessment of denoising algorithms for PC geometry. To introduce geometry errors in clean, reference PCs, impulse noise and Gaussian noise with three different strengths were added to represent three different perceptual qualities. Several outlier removal and regularization algorithms were applied to the degraded PCs. Noisy and denoised PCs were rendered on standard 2D displays by first applying a surface reconstruction method (i.e. PC converted to polygonal meshes). Also, several objective quality metrics were selected to assess their performance in a denoising context. In a later study [24], Javaheri et al. performed the subjective and objective quality assessment of the geometry of compressed PCs. In this case, the popular Point Cloud Library (PCL) octree and graph-based codecs, with two very different types of associated distortions, were used. The rendering was performed with a point-based representation, recoloring each decoded point with the original color attributes. In both these works, PCs were visualized on a 2D display and a Double-Stimulus Impairment Scale (DSIS) method was used for subjective quality assessment.

In [14], Alexiou et al. performed a subjective quality assessment study of the PC geometry for two types of degradation, octree pruning and Gaussian noise, thus generating PCs with different quality levels and artifacts. An augmented reality (AR) headset was used to visualize simple PC objects without color from different perspectives (user could move around the object). It was concluded that objective metrics could perform well for Gaussian noise but underperform for PCL-like...
compression artifacts. In [15] and [16], Alexiou et al. also performed a subjective test with the same data as in [14] and the same distortion types but visualized on a 30-inch 2D display. In both cases, color was not used and user interaction was allowed; a simple rendering method with unit size points was selected. In [15], the impact of adopting two different subjective test methodologies, Absolute Category Rating (ACR) and DSIS, was studied through their comparison. The DSIS methodology was found more consistent and with lower confidence intervals and, thus, it was used later in [16]. In [17], Alexiou et al. performed a subjective study to evaluate the PC geometry quality using an octree pruning based codec. Before rendering, a Poisson surface reconstruction algorithm was used to obtain a mesh from the decoded PCs. In this case, no interaction was allowed with the content and the subjective experiment also followed the DSIS methodology. It was found that most PC objective quality metrics have a low correlation with the subjective scores and the 3D surface reconstruction algorithm plays a crucial role on the quality scores obtained.

In [18], Alexiou et al. performed two subjective tests to study the impact of visualization on the subjective quality assessment of PCs. The first test used a 30-inch 2D display and the second an AR headset. As before, geometric artifacts associated to octree coding and Gaussian noise were used. The test methodology was DSIS and interaction by users was not allowed. In any case, the correlation between quality scores obtained with different visualization devices was rather high, notably statistically equivalent for Gaussian noise.

In [19], Alexiou et al. conducted a subjective quality evaluation to assess the quality of compressed PCs rendered as mesh objects in several types of 3D displays, from passive stereoscopic to auto-stereoscopic displays. Geometry degradations in the form of octree pruning were evaluated in the absence of color. The results obtained with 3D displays have a strong correlation with the results obtained with 2D displays for the same content. However, it was also found that the rendering method may play a significant role in this evaluation. Also, Alexiou et al. have benchmarked objective quality metrics for PC data represented by octree pruning and corrupted with Gaussian noise [20]. Both DSIS and ACR methodologies were used in separate sessions. It was found that the correlation between subjective and objective quality scores was low for distance-based objective metrics for octree-based compression artifacts but better correlation performance could be achieved with metrics considering the normal at each point.

In [25], Christaki et al., performed a subjective study for simple PCs, that were converted to meshes and coded with suitable open-source mesh codecs. While some of the test PCs are common with the PCs often used in previous subjective quality evaluation studies (e.g. Bunny) others were obtained with a platform designed for 3D human capture (with multiple Kinect devices). In [25], a variant on the pairwise subjective test methodology was used for evaluation with three stimulus presented simultaneously. Overall, three mesh codecs were considered, and content was displayed with a VR application in a head-mounted display. They concluded that usual 3D mesh quality metrics have a low correlation performance in this scenario and the 3D mesh surface reconstruction method plays an important role. Finally, Dumic et al. presented in [26] the state-of-the-art on PC subjective quality evaluation as well as a summary on the available PC objective quality metrics.

In many of studies reviewed above, it is concluded that the rendering process, applied after decoding, can have a significant impact on the perceived quality by the users; however, there is no solid assessment or quantification of the differences between rendering methods. Moreover, realistic distortions produced by relevant coding solutions are not often used, e.g. compression artifacts have been artificially simulated by noise addition or coding solutions that are much less efficient, compared to the MPEG PC codecs. Also, all the previous studies on PC quality assessment do not follow a common set of test conditions, such as those defined by the MPEG and JPEG standardization bodies. Finally, many previous works just focus on a single type of quality metrics. These limitations and simplifications are overcome by this paper which precisely targets to study the impact of the rendering process on the perceived quality and objective metrics accuracy for recent, efficient coding solutions, under meaningful test conditions, for a wide range of objective quality metrics. This should guide future developments in the areas of subjective and objective PC quality assessment.

III. POINT CLOUD CODING AND RENDERING SOLUTIONS

Considering the paper objectives, three well-known state-of-the-art PC codecs and three widely used rendering solutions used later for subjective and objective assessment are described; moreover, typical PC coding artifacts are also characterized.

A. Selected Point Cloud Coding Solutions

This section reviews some relevant and representative PC coding solutions available in the literature that will be later used for subjective and objective quality assessment. As mentioned before, only the geometry component will be addressed. Naturally, the MPEG G-PCC and V-PCC codecs, currently under development, are the most relevant for this work as they are the most recent and efficient PC coding solutions available. These codecs are part of the MPEG-I set of standards, which aim to design key technologies for immersive media.

Considering the above context, the PCL, MPEG G-PCC and V-PCC codecs were selected. These codecs represent the three most relevant ways to structure PC data for coding purposes, namely tree, surface and patch, respectively. A tree is a data structure where the points are organized in a tree, e.g. octrees, kd-trees; a surface is a data structure where the points are represented with a parametrized surface model (e.g. represented as a set of triangles); finally, a patch clusters points into groups with some size, which is suitable for 3D to 2D projections. Naturally, these PC codecs produce different types of geometry artifacts, such as loss of geometric detail, geometric deformations, holes creation and other geometric distortions, e.g. curved surfaces represented by a set of planes.

1) PC Coding with Tree Structures

The PC coding solution selected for this class is the popular PC codec public available in the Point Cloud Library [27], a large scale, open project for 2D/3D image and PC processing. To facilitate the compression of geometry data, this codec
represents the PC 3D coordinates and its attributes with an octree structure [28]. The PCL PC codec is often used as benchmark since it can handle unorganized PCs of arbitrary size/density acquired with many types of sensors and has low encoding and decoding complexity.

In PCL, each octree node corresponds to a voxel in 3D space. The root node corresponds to a voxel that contains all points of the PC, the so-called PC bounding box. Then, starting from the root node, each voxel is divided iteratively into 8 voxels with the same size; naturally, a node is not divided if the corresponding voxel is not occupied. The occupancy of a node is represented with a single byte that signals the occupied child nodes up to the leaf voxels. By traversing the octree in breadth-first order, a stream of occupancy bytes is created, thus allowing an efficient representation of the PC geometry.

The decoded quality is determined by the octree depth, which indirectly specifies the minimum voxel size; this corresponds to a pruned octree, since the octree will not have the full depth. When the PC is decoded, all the points inside an occupied voxel are represented with just one point at the voxel center. The statistics of the occupancy bytes are exploited by an entropy encoder (range coder [29]) that takes into account the specific (non-uniform) symbol frequencies. The PCL v.1.8 version was used as the reference software for the experiments reported here. In these experiments, no point detail coding is performed to refine the geometry within the leaf voxels.

2) PC Coding with Surface Models

The PC coding solution selected for this class is the MPEG G-PCC codec, which is capable of lossy and lossless coding of large PCs, with spatial random access, view dependent processing, packetization, and scalability [30]. As the PCL octree-based codec, the G-PCC codec is also based on octree decomposition to code the PC geometry but extends this coding paradigm with a parameterized surface model. As in PCL, a pruned octree is used but the geometry of the points at each leaf voxel is not represented by the voxel center; instead, a set of triangles is used to represent a surface formed by these points.

In G-PCC, the input PC data is first voxelized such that the resulting coordinates lie in the cube \([0, 2^d - 1]^3\) and all points are represented by the voxel center; \(d\) corresponds to the octree (full) depth parameter (defined \(a\ priori\)). Then, a pruned octree is created, from the root down to some specific octree level (\(\ell\)), which must be smaller or equal than the octree depth; for lossless coding, level must be equal to the octree depth. If \(\ell\) is smaller than depth, a polygonal representation is used to represent the points, which is known as TriSoup, an amalgam for Triangle Soup. This means that the limited depth octree is complemented with additional geometry information within groups of voxels, called blocks; this additional geometry is represented by vertices, corresponding to the intersections of the surface with some edges of the block (in this case at most 12 vertices). This set of vertices is sufficient to reconstruct a surface, corresponding to a non-planar polygon passing through the vertices. TriSoup uses triangles to represent these polygons, as they are particularly friendly to standard graphics processors. The TMC1 v.1.1 version of the G-PCC reference software was used for the experiments reported in this paper.

3) PC Coding with Patch-based Projection

The PC coding solution selected for this class is the MPEG V-PCC codec, which targets dynamic PC coding and performs a 3D to 2D mapping of both the geometry and color components [31]. Thus, depth and texture images are created and can be coded with any video codec, notably a High Efficiency Video Coding (HEVC) standard-compliant codec [32].

In the first step, the PC is decomposed into several patches with smooth boundaries, while minimizing the reconstruction error. PC points are clustered according to the relation between their normals and the normal directions of six predefined oriented planes (forming a 3D bounding box). Then, patches are extracted from these clusters using a connected component technique and mapped onto a 2D grid using a packing process which attempts to minimize the unused space. Each \(T\times T\) (e.g., \(16\times 16\)) block in the grid is associated with a unique patch. After the packing, geometry (depth) and texture maps are created and the empty spaces between patches are filled using a padding process to obtain a smooth image (easier to code). These maps are passed to an HEVC encoder, which exploits the spatial and temporal correlations in a very efficient way. An occupancy map used to determine whether a grid cell is occupied or not is also coded to determine which 3D points are decoded. The TMC2 v.2 version of the V-PCC reference was used for the experiments reported in this paper.

B. Selected Point Cloud Rendering Solutions

PC rendering is the process of producing a visual representation that can be consumed by users using an available display, e.g. conventional 2D, stereo, auto-stereoscopic, head mounted displays, etc. [33]. Since it effectively selects the information to be seen, the rendering process has a significant impact on the quality perceived by the user. In this section, the rendering solutions selected for the experiments reported in this paper are briefly described.

Regarding PC rendering, there are two main approaches; the first, directly uses the PC data (point-based) while the second converts the PC data into another representation format, very commonly a surface, e.g. a polygonal mesh. The decision on the rendering approach to adopt mostly depends on the application requirements which may be very different.

The PC conversion to another representation format more rendering friendly may bring some loss of information and, in some cases, it may not even be possible due to the complexity of the visual scene in terms of geometry or the low PC density. By directly rendering PCs, massive amounts of points can be visualized. Rather often, these PCs do not fit into the available memory and require special algorithms to stream, process and render only a small subset of the entire PC data. This is easier to perform with a point-based model due to the lower complexity associated to the rendering process in comparison to a polygonal mesh representation where surface reconstruction and interpolation are usually needed.

Independently of the rendering approach, a geometry shader with some primitives is employed to construct the final image shown to the user. In this context, the geometry shader is responsible for the creation of appropriate levels of light, darkness, and color within an image [34]. For PCs only with
geometry, the shading is commonly performed with a single color; otherwise, color attributes are used for each point or vertex. Moreover, primitives are the simplest (atomic) elements that are combined to create the 3D impression of surface in the final displayed content.

1) Point-based Rendering without Color Attributes

Point-based rendering algorithms use a set of discrete points that may be irregularly distributed and simple rendering primitives or image or object space interpolation procedures to obtain a 2D image. The main advantage of this rendering approach is that it can achieve high levels of realism and is adequate for complex objects, such as trees, feathers, smoke, water, etc. In addition, point based rendering simplifies the rendering process and typically requires less memory and computational power due to the lack of connectivity information.

In this approach, simple and fast to render primitives are selected, such as circles, squares, spheres, cubes. Based on the PC density and distance to the virtual camera (zoom level), the size of the primitives can be manually or automatically adjusted to create the impression of a surface; in the automatic case, connectivity information between points is usually computed to determine the primitive size [24]. The definition of an appropriate size for the primitive is rather important to reduce the appearance of empty spaces (holes) between points (size too small) or aliasing artifacts (size too large). In this work, the primitive selected for rendering was a square because they are similar to the smallest element of a 2D image (pixels) and the point size was set to the minimum value able to fill the 3D space between points completely, thus avoiding holes.

Regarding shading, color attributes were not used, in order the impact of geometry distortions may be assessed without any additional component. The human visual system can easily and accurately derive the three-dimensional orientation of surfaces by using variations in the image intensity alone [35]. To obtain the normals, a (best fitting) plane was used as the local surface model and an automatic estimation for the neighborhood radius was used, as suggested in [17]. This automatic estimation helps to find a suitable radius as a too small radius may result in some points having an invalid normal and a too large radius may result into smoothed edges. By fitting a local surface, only the direction of the normal can be computed and, thus, the orientation of the normal was determined with the minimum spanning tree algorithm [36]. This type of rendering approach will be designated as RPoint in the following.

2) Point-based Rendering with Color Attributes

The second rendering solution is still point-based but uses also the available color attributes and thus for this reason, it will be designated as RColor in the following. In RColor, the RPoint rendering method is again applied but the point color attributes are used. This means that the surface is still represented with points and displayed with the same primitives but with the color obtained during the PC acquisition process. While the color attributes correspond to the real color of the objects, they are still influenced by the specific light conditions that have occurred during their acquisition. However, in the final rendered image, some colors can be interpolated, e.g. between points, to avoid aliasing. Moreover, since the captured color also conveys the object depth, it may mask some geometric distortions of the surface. On the contrary, distortions may be more visible at object boundaries, which give the user, the shape perception of the objects in the visual scene.

In this work, to isolate the impact of geometric distortions, the color attributes are not compressed and thus the original color is used to recolor the decoded PC (which may have or not the same number of points as the original PC). In the adopted RColor rendering method, no relighting is performed to preserve as much as possible the color fidelity of the PC representation.

3) Mesh-based Rendering

The first step in the mesh-based rendering approach, hereafter designated as RMesh, is to create polygonal meshes with a surface reconstruction algorithm, such as the Poisson Surface Reconstruction [37]. This means that rendering is performed with a set of vertices along with their connectivity to obtain a closed surface very precisely defined.

The advantage of this rendering method is that, independently of the distance to the object (or scene) or the PC density, a seamless surface is obtained; this may not occur with point-based rendering since the quality is associated to the number of points describing the surface and the distance between the viewer and the object. The disadvantage of this rendering method is that it requires surface reconstruction, which usually removes high frequency geometric details [38] (smooth surfaces are obtained). It is important to note that surface reconstruction from complex surfaces is not always straightforward, it may not always be successful and can even require some user intervention. After surface reconstruction, the polygonal mesh needs to be rendered, usually with some shading algorithm [39][40]. There are several mesh rendering techniques performing shading, reflection, refraction and indirect illumination, and able to improve (when properly applied) the quality of the rendered data.

In this work, the procedure to reconstruct the surface proposed in [17] was followed. The Poisson Surface Reconstruction algorithm, available in the popular CloudCompare [41] software, was selected with default parameters. The estimation of the normal vectors was performed as for the RPoint solution; no color attributes were used to be able to directly assess the impact of the geometric artifacts in the perceived quality.

C. Coding Artifacts

This section describes the distortions associated with each of the PCC selected solutions. A characterization of the artifacts is important to understand the perceptual impact in the subjective tests and the limitations of the available objective metrics.

1) PCL Codec

In the PCL codec, as the target bitrate decreases (lower octree depth), the number of decoded points also decreases since all points inside a voxel are represented by just one point at the voxel center. The consequence is an increase of the distance between decoded points and thus lack of detail. When PCL decoded PCs are rendered, in any rendering solution, the lack of detail (i.e. points) results into a pixelated (or overly sub-sampled) decoded PC. An example of the artifacts produced with PCL coding at low rate is illustrated in Fig. 2, for the Loot PC for all
rendering solutions. As shown, the rendered PCs suffer from lack of resolution and are rather pixelated (RPoint and RColor) or lack detail (e.g. face and hands in RMesh).

2) MPEG G-PCC Codec

The MPEG G-PCC codec prunes the octree at some specific depth and after creates a surface representing all points in that depth with more precision. The rendering artifacts produced are very different from PCL, since the number of decoded points is no longer reduced. An example of the artifacts produced by G-PCC at low rate is illustrated in Fig. 3 for the Egyptian Mask PC for all rendering solutions. The geometric artifacts essentially come from the TriSoup process which may create false edges at the boundaries of the blocks or triangles; for low rates, these triangles may be visible. Moreover, when the PC is sparse in some region, the TriSoup process may cause artificial holes (with polygonal shapes) or even an increase in the size of holes already present in the original PC.

3) MPEG V-PCC Codec

In MPEG V-PCC, PC data is coded with traditional prediction and 2D transform tools. The more visible rendering artifacts correspond to blockiness and the creation of false edges, often associated to the directional Intra prediction modes. An example of the rendering artifacts produced by V-PCC is illustrated in Fig. 4 for House without a roof PC for all rendering solutions; false edges are visible, mostly for RPoint rendering.

However, large deformations on the geometry typically do not occur, even for low rates, and some of them can be mitigated with RColor rendering. Another type of artifact typically occurring with V-PCC coding is the lack of points at the patch boundaries.

IV. PC Rendering after Coding: Subjective Quality Assessment Study

In this section, the creation of the visual content for the subjective experiments is described along with the test setup and the experimental results. The analysis of these results will allow to assess the visibility of distortions of each codec under different rendering approaches.

A. Test Conditions

Six static PCs with different characteristics have been selected from the voxelized data in the MPEG content repository [42], notably Egyptian mask and Frog from the class inanimate objects, Facade9 and House without a roof from the class buildings and facades, and Long dress and Loot from the class people. Table I shows the PC name, number of points, coordinates precision, category and PSNR peak for each of the selected PCs while Fig. 5 shows the original PCs with RColor rendering.

| PC Name      | No. Points | Precision | Category            | PSNR Peak |
|--------------|------------|-----------|---------------------|-----------|
| Egyptian Mask| 272,684    | 12 bit    | Inanimate Objects   | 4095      |
| Facade9      | 1,596,085  | 12 bit    | Facades & Buildings | 4095      |
| Frog         | 3,614,251  | 12 bit    | Inanimate Objects   | 4095      |
| House wo. roof| 4,848,745 | 12 bit    | Facades & Buildings | 4095      |
| Loot         | 805,285    | 10 bit    | People              | 1023      |
| Longdress    | 857,966    | 10 bit    | People              | 1023      |

The selected PCs were coded with the three selected PC codecs, at three different rates, to obtain decoded PCs with three different perceptual qualities, labelled as Low (L), Medium (M) and High (H). The selected codecs represent three different coding paradigms, notably PCL for tree structures, MPEG G-PCC for surface models and MPEG V-PCC for projection-based coding. For each of the MPEG PC codecs, three different rate points have been selected based on the suggested coding parameters in the MPEG Common Test Conditions (CTC) [43] for lossy coding. These rate points resulted into three
distinguishable qualities, ranging from low to high. For PCL, the 
occtree depth parameter was defined in a way to obtain a similar 
range of qualities compared to V-PCC.

Table II shows the coding parameters used for the PCL and 
MPEG G-PCC codecs. For G-PCC, the octree depth establishes 
the PC precision (after the encoding voxelization step). The level 
parameter corresponds to some octree layer after which a 
polygonal representation is used. For PCL, the octree depth (OD) 
is set indirectly, using the PCL Octree Resolution (OR) parameter 
which corresponds to the size of the voxel computed as \( OR = 2^{(P-OD)} \), with \( P \) as PC precision (defined in Table I). Table III 
shows the MPEG V-PCC HEVC quantization parameter (QP) 
used for depth map coding (note that no texture coding is 
performed) and B0 is the occupancy map precision. For V-PCC, 
all the test material was voxelized to 10-bit precision.

| Table II | Test Conditions for PCL and G-PCC Codecs. |
|----------|------------------------------------------|
| PC       | PCL                                      |
|          | G-PCC                                    |
|          | Octree depth | Octree depth | Octree Level |
| L | M | H | L/M/H | L | M | H |
| Egyptian Mask | 7 | 8 | 9 | 6/7 | 5 | 6 | 7 |
| Frog | 8 | 9 | 10 | 11 | 7 | 8 | 9 |
| House wo. Roof | 8 | 9 | 10 | 11 | 7 | 8 | 9 |
| Facade9 | 8 | 9 | 10 | 11 | 7 | 8 | 9 |
| Loot | 7 | 8 | 9 | 10 | 6 | 7 | 8 |
| Longdress | 7 | 8 | 9 | 10 | 6 | 7 | 8 |

| Table III | Test Conditions for V-PCC Codec. |
|-----------|----------------------------------|
| Quality   | Low | Medium | High |
| QP        | 32  | 24    | 16   |
| B0        | 4   | 4     | 4    |

B. Test Sessions

The subjective quality assessment was performed in three test 
sessions, each using a different PC rendering approach. Following Section III.B, the test sessions have been labelled as:

1. RPoint session: PCs are rendered with point-based rendering with point shading without color attributes.

2. RColor session: PCs are rendered with point-based rendering with the original color (by recoloring) and no shading.

3. RMesh session: PCs are rendered with mesh-based rendering with surface shading without color attributes.

The decoded PCs were rendered with the CloudCompare PC 
processing software for the three selected rendering solutions. For the RPoint, RColor and RMesh rendering solutions, the point size, 
normal estimation and surface reconstruction were performed as 
described in Section III.B. The lighting conditions, which 
influence the shading process in RPoint and RMesh, correspond 
to the default conditions, this means ambient light source (sun 
light) and no spotlight. A simple camera path rotation around the 
object was used to create a 2D rendered video, thus allowing to 
have a complete visualization of the entire PC object or visual 
scene. For some PCs (e.g. Facade9), no geometry was acquired 
for the back side and, thus, the rotation path was restricted to the 
frontal part of the object.

C. Subjective Quality Assessment Methodology

The rendered videos generated from the original and decoded PCs 
were viewed in sequence and scored by each subject with the play 

doing the videos for the influence the shading process 
processing software for the three selected rendering solutions.

3. 2. 1.

performed used for depth map coding (note that no texture coding is 
performed) and B0 is the occupancy map precision. For V-PCC, 
all the test material was voxelized to 10-bit precision.

The advantage of rendering decoded PCs to video 
sequences is that all subjects in the subjective test see the same 
parts of the PC exactly in the same way, thus obtaining more 
reliable subjective assessment scores.

The PCs selected for the subjective study have rather different 
characteristics. Due to the acquisition process, some original PCs 
can be rather noisy, e.g. MPEG cultural heritage and buildings 
sub-category may have holes, outliers or even positioning errors. 
Also, the density (number of points per unit volume) of the 
original PC may have a significant impact on the perceived 
quality of the original rendered PC. These two factors may affect 
the subjective scores given by the subjects. Since these issues 
affect both the original and decoded PCs, the DSIS subjective test 
methodology was selected for all the test sessions of this 
subjective study. Thus, subjects visualize first the original and 
then the decoded rendered PCs, and score the decoded PC 
relatively to the original, which allows to mitigate the impact of 
acquisition artifacts and other original PC characteristics.

There were 20 subjects participating in each test session with 
18 people participating in all the three sessions and four people in 
one or two sessions. At the beginning, the goal of the subjective 
assessment experiment was explained to the subjects and they 
were asked to participate in a short training session just before 
each of the test sessions. For the training sessions, the Statue 
Klimt PC from the same MPEG repository was used.

The full set of rendered PCs was organized into six rounds per 
session with each round including all PCs with one of the three 
levels of quality. According to Recommendation BT-500.13 [44], 
the subjects see first the reference/original rendered PC and after 
the impaired/decoded rendered PC and score the later in a 1-5 
scale associated to five quality levels, notably very annoying, 
annoying, slightly annoying, perceptible but not annoying and 
imperceptible. Each session had a duration of approximately 28 
minutes, considering the training and scoring times. To avoid that 
the results of one session influenced the results of another session, 
a minimum of 48h between test sessions was respected.

For each session, outlier subjects were identified based on the 
collected scores, following the procedure in BT.500-13 [44]; only 
one outlier was identified in the RMesh session. After, the average 
of all scores across the subjects were computed for each test PC, 
thus obtaining a MOS score for each PC under evaluation. The 
subjective scores for the three test sessions along with the original 
and decoded rendered PCs are publicly available at [45] and thus 
may be used by the research community.

D. Experimental Results and Analysis

The focus of this section is on the study of the impact of 
different PC rendering solutions on the user perceived quality for 
PCs compressed with different coding paradigms and, thus, with 
different coding artifacts. Moreover, the obtained subjective 
scores are analyzed to assess the visibility of the different coding 
artifacts. The subjective scores obtained for the three test sessions 
will be the basis for this study.

1) Impact of Rendering on Perceived PC Quality

This section studies the impact of the three rendering solutions 
on the perceived PC quality. Note that, within each session, the 
rendering methods were not mixed and thus the subjects
evaluated rendered videos from decoded PCs for each rendering solution independently.

Fig. 6 shows the 54 MOS scores for all PCs within each test session (each associated to a rendering solution). In Fig. 6, the MOS scores are sorted in ascending order, thus from lower to higher scores/qualities; each score is labelled with a rendered PC index and corresponds to a coding condition. To identify which are the most frequent MOS scores per session (data not shown in Fig. 6), Fig. 7 shows the MOS scores distributions (number of votes) given by the subjects in the three rendering sessions.

RColor rendering: For RColor rendering, the original texture contains natural shading information, acquired from the light reflected by the object surface. This contrasts with the RPoint and RMesh renderings which use a single color with synthetic shading and the final result depends on the accuracy of the (extracted) normal vectors (geometry only). However, it is clear that the original color captured during the acquisition is able to mask many of the geometric distortions, changing the perceived surface of the objects. Also, the texture details are able to hide geometric distortions since the human visual system is less sensible to high frequencies; this will cause the subjects to perceive less distorted shapes and, thus, better MOS scores are given in the RColor session. In fact, in the RColor session, most of the scores are ‘4’ and ‘5’ as shown in Fig. 7, which means that most of the decoded PCs were considered to have high quality. In this case, the most visible geometric distortions are limited to the object boundaries.

In summary, rendering with high quality color attributes masks the geometric distortions and results in higher perceived PC qualities. Rendering with RMesh increases the quality regarding RPoint rendering but, due to the smoothed details, it may impair or modify the PC in unintended ways.

2) Impact of Rendering on the Coding Artifacts Visibility

This section studies the impact of the three rendering solutions on the visibility of the coding artifacts associated to the three selected codecs. With this purpose in mind, the MOS scores for the three PC codecs and the three rendering solutions are shown in Fig. 8. This PC codec presentation of the MOS scores, more granular compared to Fig. 6, allows comparing the impact of the rendering solution on the final perceived visibility, when different coding artifacts are present. From Fig. 8, it is clear that the MOS scores distribution for each rendering approach is not similar for all codecs. The main conclusion is that the different coding artifacts are not equally visible for all rendering approaches, i.e. the sensibility of each rendering solution to different coding artifacts is different and, thus, these two processing components may have to be appropriately matched.

RPoint rendering: The geometry coding distortions are more visible for RPoint rendering since RMesh and RColor have mechanisms to mitigate the visual impact of the coding artifacts, e.g. filtering or masking. This can be clearly observed in Fig. 6 where the coding artifacts are more visible for the curve with lower MOS scores and, thus, as shown in Fig. 7, more ‘1’, ‘2’ and ‘3’ votes are obtained for RPoint compared to RMesh and RColor.

RMesh rendering: As shown in Fig. 7, RMesh rendering has higher MOS scores (and less low MOS scores) than RPoint rendering. This can be explained by the fact that RMesh rendering includes a surface reconstruction process (polygonal mesh creation) which smooths the PC and makes the coding distortions less visible, somehow behaving as a denoising filter. However, it should be emphasized that PC edges and details are also smoothed with this type of rendering and, thus, RMesh is not able to outperform a point-based rendering solution with texture (RColor), where the points are simply rendered with a basic primitive, e.g. circles or squares. It also requires the extra pre-processing step of surface reconstruction before rendering which may be difficult to apply in some application scenarios due to the scene complexity or the PC size (number of points).
number of points than the original PCs, sometimes significantly lower. Thus, since PCL decoded PCs have lower point density, larger point sizes for \( RPoint \) and \( RColor \) rendering are needed, thus creating a down-sampling effect (perceptually unpleasant), with less accuracy both in terms of geometry and color. If a lower number of decoded points is obtained, a rather pixelated look is obtained. Although a surface is reconstructed with \( RMesh \) rendering, when the number of points is reduced, the distance between points increases, details are lost and some meshes may show geometric distortions due to the surface reconstruction process. This behavior is also illustrated in Fig. 2 where the PCL distortions are always visible regardless of the rendering solution.

**G-PCC Coding:** G-PCC distortions are less visible for \( RColor \) rendering compared to \( RPoint \) and \( RMesh \), since the color masks the surface distortions. However, false edges, holes and geometric distortions at boundaries are still visible for the severe distortion cases. Although less than for PCL, G-PCC artifacts are still annoying even after surface reconstruction. This explains the similar trend for the \( RPoint \) and \( RMesh \) scores with a small gain for \( RMesh \) rendering mainly due to the smoothing of distortions which closes some holes visible in \( RPoint \). As shown in Fig. 3, G-PCC distortions are more impactful for \( RPoint \) and less for \( RColor \) rendering.

**V-PCC Coding:** V-PCC distortions are not very visible for \( RColor \) rendering and they are also less visible for \( RMesh \) than for \( RPoint \) rendering. Since V-PCC geometric distortions are not large enough to create strong deformations, the color masks most of the geometric distortions when using \( RColor \) rendering. Due to the V-PCC projection onto 2D maps (texture and depth), and the efficient HEVC coding process, most of the surfaces are consistently represented, although with some error regarding the original surface. Moreover, the surface reconstruction-based rendering used in \( RMesh \) reduces the geometric distortions by filling holes and avoiding abrupt changes, thus offering a smoother and more visually appealing surface; these artifacts are more visible for \( RPoint \) rendering. As shown in Fig. 4, with \( RColor \) rendering, V-PCC distortions are not very visible while, with \( RMesh \), the entire decoded PC is smoother (and the impact of some distortions is reduced) compared to \( RPoint \). However, some details may be lost (e.g. in the bell tower) which may cause lower perceived quality.

In summary, PCL distortions are equally visible for all rendering solutions and thus, any rendering can be used. For G-PCC and V-PCC decoded PCs, color can mask geometric distortions and thus \( RColor \) should be used (if color is available). In addition, \( RMesh \) rendering results in a slightly better quality than \( RPoint \), since it allows to mitigate the impact of some coding artifacts, e.g., holes or false edges.

V. **PC Rendering After Coding: Objective Quality Metrics Performance Assessment**

The main purpose of this section is to evaluate the performance of several PC objective quality metrics in the presence of coding artifacts. Only metrics accounting for geometry errors are considered since this is the PC component where artifacts may cause a higher negative impact on the user quality of experience.

First, the objective quality metrics that are evaluated are presented and then the correlation between the objective metrics and the MOS scores are reported and analyzed. This will allow to understand which objective quality metrics perform better, which type of coding degradations can be more appropriately accounted and what is the impact of the rendering solution on the PC objective quality metrics accuracy.

A. **Geometry Objective Quality Assessment Metrics**

Objective quality assessment metrics for PCs are essential for several tasks, notably: i) measuring the PC quality and thus playing a part on the RD performance assessment of PC coding solutions; ii) optimizing PC coding solutions, e.g. allowing to make perceptual optimizations; iii) measuring end-to-end quality in PC streaming solutions, thus involving more than coding. In this section, the most popular geometry objective metrics for PC quality assessment adopted for this study are presented. These quality metrics are all full reference metrics and, thus, compare the original with the decoded PCs, typically with some coding artifacts. To measure the decoded PC geometry quality, correspondences are established between points in the degraded and original PCs. The following classes of metrics exploit these correspondences and can be defined by:

1. **Point-to-point (Po2Point) Objective Quality Metrics**

Point-to-point quality metrics establish correspondences for each point in the original PC A and the nearest neighbor (NN) point in the degraded PC B [46]; correspondences are computed in two directions and, thus, also from PC B to PC A.

Assuming \( \vec{e}_1(a_i, b_j) \) as an error vector between point \( a_i \) in PC A and the \( a_i \) nearest neighbor point \( b_j \) in PC B, the point-to-point error vector length, i.e. the distance \( d_{\text{Po2Point}}^{AB} \) between these two points is given by:

\[
d_{\text{Po2Point}}^{AB}(i) = \| \vec{e}_1(a_i, b_j) \|^2
\]

This distance is computed for all the points in both directions, i.e. from original to degraded PCs \( d_{\text{Po2Point}}^{BA} \) and from degraded to original PCs \( d_{\text{Po2Point}}^{AB} \), for every point. There are three main approaches to aggregate or pool all the computed errors:

- **Mean Squared Error (MSE):** Average of the squared distance between each point and their corresponding nearest neighbor, for all points, as defined in:
MSE_{AB} = \frac{1}{N_{A}} \sum_{\forall i \in A} d_{Po2Point}^2(i) 
\text{(2)}

where \( N_{A} \) is the number of points in PC A.

- **Hausdorff (HAUS) distance:** Maximum for all points of the MSE distance as defined in:

\[
\text{HAUS}_{AB} = \max_{\forall i \in A} \{d_{Po2Point}(i)\}
\text{(3)}

- **Geometric PSNR:** Geometric PSNR metric defined as:

\[
\text{PSNR}_{AB} = 10 \log_{10} \left( \frac{3P^2}{\text{MSE}_{AB}} \right)
\text{ with } P = 2^{pr} - 1
\text{(4)}

where \( P \) is the peak constant value and \( pr \) the PC coordinates precision. The metrics above defined just for one direction (from PC A to B) are computed also in the other direction and, thus, the final metric value can be computed as:

\[
\text{MSE} = \max(\text{MSE}_{AB}, \text{MSE}_{BA})
\text{(5)}
\]

\[
\text{HAUS} = \max(\text{HAUS}_{AB}, \text{HAUS}_{BA})
\text{(6)}
\]

\[
\text{PSNR} = \min(\text{PSNR}_{AB}, \text{PSNR}_{BA})
\text{(7)}
\]

The PSNR metric corresponds to the Po2Point PC quality metric used nowadays by the MPEG 3DGC group in the evaluation of PC coding methods such as G-PCC and V-PCC, labelled as D1 [42].

2) **Point-to-Plane (Po2Plane) Objective Quality Metrics**

Point-to-plane metrics take into consideration the underlying object surface represented with the PC by fitting a plane to the local neighborhood of each point [47]. Considering the 3D point locations and their associated surfaces, the normal for each point is equal to the normal of the tangent plane to the surface. A point and the corresponding normal vector can, thus, determine the tangent plane for each point. As for Po2Point metrics, Po2Plane metrics are also symmetrically computed for both directions, i.e. from original to degraded and from degraded to original PCs. However, Po2Plane metrics only require the computation of normals on the original PC, which are directly used when the original PC is taken as reference. Otherwise, if the degraded PC is the reference, the normal for each point is estimated by averaging the normals of the nearest neighbor points from the original PC.

The Po2Plane error distance between two points \( \hat{e}_{2}(a_{i}, b_{j}) \) is obtained by first computing the Po2Point error vector \( \hat{e}_{1} \), which is then projected onto the normal \( \bar{n}_{j} \). Thus, the Po2Plane distance \( d_{Po2Plane}^{BA}(i) \) that represents the error between a point and its corresponding surface is given by:

\[
d_{Po2Plane}^{BA}(i) = \| \hat{e}_{2}(a_{i}, b_{j}) \|_2^2 = (\hat{e}_{1}(a_{i}, b_{j}) \cdot \bar{n}_{j})^2
\text{(8)}
\]

MSE distance, Hausdorff distance and Geometric PSNR may then be computed with the projected error distances as for Po2Point metrics (where the error vector is not projected). In this way, the degraded PC points that are closer to the reference surface have smaller projected distances even though they are farther from the corresponding point on the reference PC. The Po2Plane PSNR metric is also used by MPEG for the evaluation of the G-PCC and V-PCC codecs, labelled as D2 [42].

3) **Plane-to-Plane (Pl2Plane) Objective Quality Metrics**

This type of objective quality metrics estimates the similarity of surfaces of the original and degraded PCs [48] to obtain a quality score. In this case, tangent planes are estimated for both the original and degraded points. As for Po2Plane metrics, tangent planes are used as a local linear approximation of the underlying object surface but, in this case, planes are estimated for both the original and degraded PCs.

Again, to compute Pl2Plane metrics, the nearest neighbor correspondences are computed in both directions. The Pl2Plane quality metrics depend on the angular similarity (or dissimilarity) between the planes, i.e. the angular difference between local planes associated to the points in a correspondence. In this case, the so-called cosine similarity measure, \( cs \), measuring the cosine of the angle between two vectors is used. The two vectors correspond to the normal vectors (perpendicular to the tangent planes) for the two points in a correspondence in PCs A and B [48], as in:

\[
 cs(i) = \cos(\theta_{i}) = \frac{\bar{n}_{a} \cdot \bar{n}_{b}}{\|\bar{n}_{a}\|_2 \|\bar{n}_{b}\|_2}
\text{(9)}
\]

where \( \bar{n}_{a} \) and \( \bar{n}_{b} \) are normals for points \( a_{i} \) and \( b_{j} \) in PCs A and B. To compute the angular difference (or distance), \( d_{Pl2Plane} \), the inverse cosine is used as follows:

\[
d_{Pl2Plane}^{BA}(i) = 1 - \frac{2\arccos(|cs(i)|)}{\pi}
\text{(10)}
\]

After determining the angular difference for all the points in the reference PC, different strategies for pooling, i.e. for aggregating the angular differences obtained for all points, can be defined. In this case, three pooling strategies were defined:

\[
\text{MAD}_{AB} = \frac{1}{N_{A}} \sum_{\forall i \in A} d_{Pl2Plane}^{BA}(i)
\text{(11)}
\]

\[
\text{MSAD}_{AB} = \frac{1}{N_{B}} \sum_{\forall j \in B} \left(d_{Pl2Plane}^{BA}(i)\right)^2
\text{(12)}
\]

\[
\text{RMSAD}_{AB} = \sqrt{\text{MSAD}_{AB}}
\text{(13)}
\]

MAD stands for mean angular difference, MSAD for mean squared angular difference and RMSAD as the square root of MSAD. As for the other types of metrics, (11)-(13) are performed symmetrically, this means in both directions. Using as reference both the original and degraded PCs, the minimum is selected as the final objective quality score.

Since PCs have different precisions (depth) for the point coordinates, the error vectors for all these metrics may not be directly comparable. To overcome this problem, all PCs are normalized to have coordinates in the [0,1] range before computing the metrics. The only exception are the PSNR for Po2Point and Po2Plane metrics which include the peak \( P \) that already plays the role of a scaling factor depending on the bit depth of each PC under evaluation.

B. **Experimental Results and Analysis**

In this section, the performance of the selected objective quality metrics will be presented and analyzed for the subjective scores obtained in the three test sessions, thus for different
rendering approaches. As recommended in [44][49], before assessing the quality metrics performance, a nonlinear logistic fitting has been applied on the objective quality scores to map them to the subjective scores scale. To assess the metrics performance, the Pearson Linear Correlation Coefficient (PLCC) is computed as a measure of the linear dependence between the MOS scores and each objective quality metric.

Table IV shows the PLCC for the 9 metrics described in the previous section, for each rendering approach, independently computed for each PC codec and also considering all codecs simultaneously (column All). Table IV highlights in bold the best correlation value between the subjective and objective scores and all the other values that do not deviate more than 0.02 from the best PLCC. With these results, the performance of each metric can be assessed for each of the three test sessions described in Section IV.B. A detailed analysis of the results in Table IV is presented in the following. First, from the perspective of the PC codec and coding distortions, after from the perspective of the rendering solution and, finally, assessing which metric performs the best and in which conditions.

1) Impact of Coding on the PC Quality Metric Assessment

PCL Coding: For PCL coded data, the Po2Plane and Po2Point metrics have the best PLCC (overall, PSNR is the best) with high correlations for all rendering approaches as shown in Table IV. As PCL controls the rate by reducing the number of decoded points, large objective errors and perceived distortions are visible for all sessions. This was expected since, when the compression ratio increases (lower rates), more and more points are discarded (due to octree pruning) and the remaining points are represented farther away from the original surface. PCL artifacts are strong enough to be visible even after the RMesh surface reconstruction.

G-PCC & V-PCC Coding: As shown in Table IV, the quality metrics performance for G-PCC is slightly lower (4 to 5%) compared to PCL and shows the highest performance for Po2Point metrics (only for RPoint and RColor sessions). Moreover, none of the selected quality metrics performs well for V-PCC coded data. The selected metrics underestimate the perceived quality after rendering for these codecs, especially for RPoint and RMesh renderings where the geometric errors are less visible, e.g. as masked by color. Since both the G-PCC and V-PCC codecs tend to add points with respect to the original PC (see Fig. 9), the density of points is increased which contributes to increase the perceived quality and, thus, the MOS scores.

However, the objective metrics are not able to account for this effect and, thus, are less correlated with the objective scores. In addition, since a wide range of values is obtained for the ratio of decoded over original number of points, notably depending on the codec (and also coding parameters), it is rather difficult to map errors to a perceptually meaningful quality metric; this makes the task of designing reliable objective quality metrics harder, especially when different types of codecs, with different coding artifacts, are jointly assessed (‘All’ column in Table IV).

The correlation of the objective metrics quality for V-PCC is much lower compared to G-PCC (cf. Table IV). The projection based V-PCC codec causes slight distortions on the geometry which are not very visible even for lower bitrates. On the other hand, G-PCC artifacts are more visible especially when the surface estimation (triangulation) process fails. Fig. 10 shows the Po2Point RMSE distance errors histogram for all the points in two PCs coded with G-PCC and V-PCC for which the same overall Po2Point PSNR (60 dB) was obtained. As shown, although the PSNR is the same, the error distribution is very different between G-PCC and V-PCC. V-PCC errors are closer to zero which makes them less perceptually visible while G-PCC errors have larger magnitudes and, thus, are more visible. This implies that G-PCC has a lower subjective quality (MOS of 1.1) than V-PCC (MOS of 3.15) even when the Po2Point PSNR objective metric computes the same quality score (in this case 60 dB). This observation happens also for other objective quality metrics, such as Po2Point and Po2Plane MSE.

In summary, the objective quality metrics performance in terms of correlation with MOS scores highly depends on the coding distortions introduced, being satisfactory when PCs are coded with PCL and G-PCC and performing poorly for the V-PCC codec. Naturally, no quality metric performs well for all codecs together, a real problem when comparing the RD performance of very different coding paradigms.

2) Impact of Rendering on the PC Quality Metrics Assessment

As previously concluded, rendering can significantly influence the perceived quality and, thus, it is important to analyze the objective quality metrics performance for different rendering solutions. The PLCC correlation over all data for all sessions is rather low (less than 78.4%) because the objective metrics cannot measure with accuracy all different types of distortions. However, as shown in Table IV, the best PLCC correlations occur for RColor rendering, for which higher MOS values were obtained. This means that geometry objective quality metrics measure the perceived quality better when color attributes are used.
The main reason is because subjects were able to better perceive quality variations for medium and high quality ranges (which occur often with RColor, cf. Section IV.D) compared to low and medium quality ranges (which occur more often with RPoint and RMesh, cf. Section IV.D). For RMesh rendering, PLCC correlations are rather low comparing to the other rendering approaches, especially for G-PCC and V-PCC codecs. For RMesh, PC data is converted to a polygonal mesh (surface reconstruction) for rendering and most the objective quality metrics do not have high correlation performance for this type of representation.

In summary, objective metrics account better distortion artifacts and are more reliable when point-based rendering (with and without color, RPoint and RColor) is used to process the decoded PCs before visualization.

3) PC Quality Metrics Correlation Assessment

**Po2Point metrics:** Po2Point metrics have a high PLCC performance for many cases but are especially better than others for the PCL and G-PCC codec (RColor and RPoint). This is because PCL and G-PCC to some extent are an octree-based PC codec and, thus, some distortions still come from the positioning error related to the 3D partitioning of space into voxels, the target of this type of metrics. The Po2Point and Po2Plane Hausdorff metrics can also reach high PLCC performance, especially for PCL data and for the RPoint session (90.07). However, Hausdorff is not a very reliable metric when different types of coding distortions (all data and G-PCC/V-PCC) are considered together. The main reason is that only the maximum error is accounted and, thus, it is too sensible to outliers; this problem has been already observed in the literature [23].

**Po2Plane metrics:** Regarding Po2Plane metrics, the performance is very similar to Po2Point metrics, slightly better for some cases, since it considers the underlying surface from which the 3D point locations were sampled. Moreover, the Po2Plane PSNR metric excels, being rather reliable and consistent for many cases (8 out of 12 coding conditions), outperforming the corresponding MSE metric. The main reason is that the peak used (computed from the geometry coordinate precision) to convert MSE to PSNR values acts as an important normalizer.

**PI2Plane metrics:** PI2Plane metrics have, in general, worst PLCC performance when compared to Po2Point and Po2Plane metrics. This is mainly because it is rather difficult to obtain reliable normals for the decoded PC, especially when some types of coding artifacts are present (e.g., holes) or when the decoded PC is rather sparse [48]. However, these metrics seem to be the best choice for the V-PCC codec (for RColor and RMesh renderings) where geometry errors mainly come from coding artifacts in the depth maps and, thus, are more consistent among different parts of the PC.

As a curiosity, the number of decoded points could also be used as an objective quality metric, see last line of Table IV. As expected, this metric performs very poorly, especially for V-PCC data where the number of decoded points is typically larger than the number of original points and critically depends on some coding parameters, e.g. B0 for the occupancy maps.

In summary, if all codecs and all renderings are considered, the Po2Plane PSNR metric is the best compromise while the Po2Plane PSNR metric comes in the second place. These metrics which are those previously selected by MPEG for the PCC Call for Proposals and also used in common test conditions [42] have the highest correlation with the perceived quality. To the best of our knowledge, this is the first time that this metrics choice has been validated with subjective scores obtained with a well-defined procedure. However, there is still significant room for improvement, especially if the goal is to achieve the same level of performance that past quality metrics (e.g. SSIM based) have obtained for 2D image and video representations.

VI. CONCLUSIONS

The main objectives of this paper are to study the impact of the rendering process on the perceived quality of decoded PCs and the performance of available PC geometry objective quality metrics. To achieve these objectives, three representative PC coding solutions and three PC rendering solutions were used as well as a wide set of objective quality metrics. The subjective experiments suggest that geometric coding distortions can be masked by using the color attributes and (to a less extent) by
Moreover, the experimental results and conclusions presented can guide the development of new subjective quality methodologies as well as objective point cloud quality metrics.

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