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JPEG Pleno: Providing representation interoperability for holographic applications and devices

Peter Schelkens[1,2] | **Touradj Ebrahimi**[3] | **Antonin Gilles**[4] | **Patrick Gioia**[4,5] | **Kwan-Jung Oh**[6] | **Fernando Pereira**[7] | **Cristian Perra**[8] | **Antonio M. G. Pinheiro**[9]

[1]Department of Electronics and Informatics, Vrije Universiteit Brussel, Brussel, Belgium.

[2]Digital and User-centric Solutions, IMEC, Heverlee, Belgium.

[3]Multimedia Signal Processing Group, Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

[4]Institute of Research & Technology b<>com, Rennes, France.

[5]Orange Labs, Cesson-Sevigne, France.

[6]Broadcasting & Media Research Laboratory, Electronics and Telecommunications Research Institute, Daejeon, Rep. of Korea.

[7]Instituto Superior Técnico, Universidade de Lisboa—Instituto de Telecomunicações, Lisboa, Portugal.

[8]Department of Electrical and Electronic Engineering, UdR CNIT, University of Cagliari, Cagliari, Italy.

[9]Universidade da Beira Interior and Instituto de Telecomunicações, Covilha, Portugal.

Correspondence
Peter Schelkens, Department of Electronics and Informatics, Vrije Universiteit Brussel, Brussel, Belgium.
Email: peter.schelkens@vub.be

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Guaranteeing interoperability between devices and applications is the core role of standards organizations. Since its first JPEG standard in 1992, the Joint Photographic Experts Group (JPEG) has published several image coding standards that have been successful in a plethora of imaging markets. Recently, these markets have become subject to potentially disruptive innovations owing to the rise of new imaging modalities such as light fields, point clouds, and holography. These so-called plenoptic modalities hold the promise of facilitating a more efficient and complete representation of 3D scenes when compared to classic 2D modalities. However, due to the heterogeneity of plenoptic products that will hit the market, serious interoperability concerns have arisen. In this paper, we particularly focus on the holographic modality and outline how the JPEG committee has addressed these tremendous challenges. We discuss the main use cases and provide a preliminary list of requirements. In addition, based on the discussion of real-valued and complex data representations, we elaborate on potential coding technologies that range from approaches utilizing classical 2D coding technologies to holographic content-aware coding solutions. Finally, we address the problem of visual quality assessment of holographic data covering both visual quality metrics and subjective assessment methodologies.

KEYWORDS
coding, compression, holography, JPEG Pleno, quality assessment, standardization

1 | INTRODUCTION

Tremendous progress has been achieved in the way that consumers and professionals capture, store, deliver, display and process visual content. There is a constant acceleration in the creation and usage of images in all sectors, applications, products, and services. Over the past 30 years, the Joint Photographic Experts Group (JPEG) has offered

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image coding standards to cope with challenges in new and emerging imaging applications. This effort has resulted in a series of successful and widely adopted coding specifications and file formats leading to the JPEG and JPEG 2000 families of image coding standards, as well as the more recent JPEG XR, JPEG XT, JPEG Systems and JPEG XS families of image coding standards.

JPEG Pleno is a recent standardization initiative by the JPEG committee. Acknowledging that imaging markets have known a steady and exponential evolution in supported resolutions over recent decades, which was mainly driven by Moore's law, one can observe the maturing of technologies that are giving rise to an unprecedented and heterogeneous range of new digital imaging devices. HDR and 3D image sensors, burst-mode cameras, light-field sensing devices, and holographic microscopes enable new capture and visualization perspectives, which are driving a paradigm shift in the consumption of visual content: moving from a planar, 2D world, towards imaging in volumetric and contextually aware modalities. This paradigm shift has the potential to be as disruptive for the imaging markets as the migration from analogue to digital, three decades ago. The JPEG Pleno standardization effort aims to define a series of widely adopted specifications that will define a common format for coding of new and emerging modalities in imaging applications and contribute to the emergence of an ecosystem by facilitating interoperability among devices, products, and services.

In Section 2, we will discuss the overall JPEG Pleno framework, the most prominent use cases for holographic coding and derived requirements. Subsequently, in Section 3, the state-of-the-art in terms of holographic coding is provided, after discussing the main representations for holographic data, and the main associated challenges are derived. To test coding technology, representative test data, suitable quality metrics, and a reproducible subjective quality assessment procedure must be defined. Section 4 covers these aspects. Finally, the next steps to be taken in the standardization process are provided in Section 5 and conclusions are drawn in Section 6.

2 | JPEG PLENO

2.1 | Overall framework

It is well recognized that major progress has been achieved in recent decades in the way that consumers and professionals are capturing, storing, delivering, displaying, and ultimately enjoying images using the popular and largely deployed 2D representation model. In fact, there is a continuous acceleration in the creation and usage of images in all sectors, applications, products, and services, and JPEG standards have played a major role in this exhaustive deployment.

In October 2014, JPEG launched the ground work for the so-called JPEG Pleno initiative following the acknowledgement of major recent developments in the capture, representation, and display of visual information [1,2], which required new standards adopting a representation paradigm where images should be consumed as volumes rather than planes. “Pleno” is a reference to “plenoptic,” which is a mathematical representation model that considers the usual luminance and color information of any point within a scene, and adds directional information about how this luminance and color change when observed from different positions. In fact, this theoretical representation model implies a clear move from a 2D to a powerful 3D modeling paradigm.

Considering the advances in the sensors, processing and displays, JPEG has decided to put special emphasis on three major plenoptic modalities, notably light fields, point clouds and holography, which may be mutually converted from one to another. The selection of these multiple, convertible modalities is related to the different requirements of the relevant uses cases, which may find one to be more friendly, as each offers different and at times complementary features and functionalities. The JPEG developments regarding these imaging modalities, while occuring in parallel, do not happen at the same speed, but rather depending on the specific industry needs and technological maturity.

It is a strong wish of JPEG that the specified technologies are made available under royalty free conditions, as it has been the case in previous JPEG standards.

To reach its goals, the JPEG Pleno is organized in several parts, each with a specific, well identified role (see Figure 1):

- *Part 1—Framework:* Single informative part that targets the definition of the overall JPEG Pleno framework, and thus setting the big picture and the landscape for the normative parts [3].
- *Part 2—Light Field Coding:* Specifies light field coding technologies and metadata; this is the most advanced part as of July 2018, following a Call for Proposals issued in January 2017 [4] with assessment of proposed technologies in July 2017. In July 2018, a Verification Model was issued with a coding architecture based on the JPEG 2000 coding of some reference views and the disparity-based synthesis of the remaining views, eventually with further residual coding [5,6]. Since JPEG Pleno adheres to a box-based file format, for which main principles are specified in JPEG Systems, Part 2 also specifies the JPEG Pleno Light Field box format, which may include the encoded light field information, configuration parameters, and calibration metadata. This part may also include the so-called JPEG Pleno superbox, which

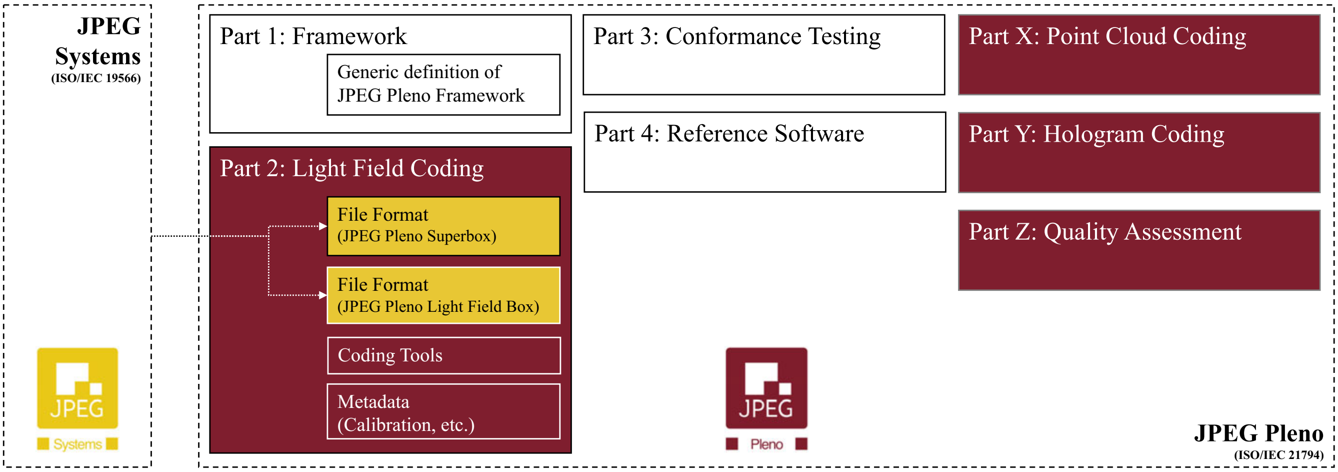

FIGURE 1 JPEG Pleno standards organization

should contain any type of JPEG Pleno data as well as complementary metadata; however, the exact part positioning of this superbox specification is still under discussion.

- *Part 3—Conformance Testing:* Specifies the processes to check the conformance of implementations of normative parts of JPEG Pleno.
- *Part 4—Reference Software:* Provides a non-optimized implementation of the specified technology, including non-normative parts, where needed, to achieve a functional solution.

Following the designed framework, it is expected that other parts will follow, notably:

- *Part X—Point Cloud Coding:* Should specify point cloud coding technologies and associated file format elements and metadata; in July 2018, the identification of use cases and definition of associated requirements was still ongoing [7].

> In summary, JPEG Pleno intends *to provide a standard representation framework to facilitate the capture, representation, and exchange of light field, point cloud and holographic imaging modalities*. This goal requires the specification of system tools, coding tools, and appropriate metadata, not only for efficient compression but also for data and metadata manipulation, editing, random access and interaction, protection of privacy and ownership rights, as well as security management. This framework should offer more than the sum of its parts by allowing them to be flexibly combined, exchanged, and exploited in a single scene or processing pipeline.

- *Part Y—Hologram Coding:* Should specify holographic data coding technologies and associated file format elements and metadata; in July 2018, the identification of use cases was still ongoing [8].
- *Part Z—Quality Assessment:* Should specify quality assessment protocols as required by the novel imaging

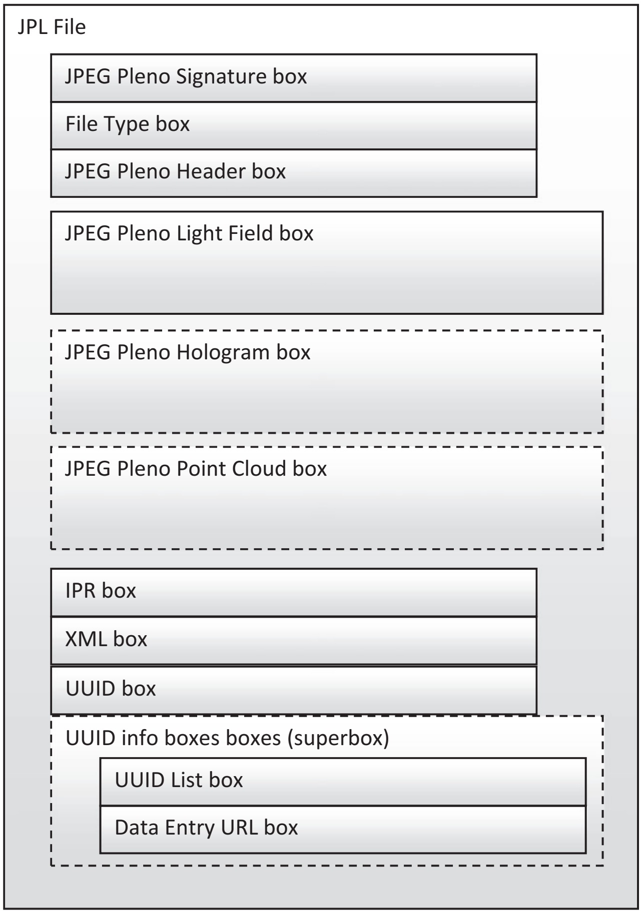

FIGURE 2 Conceptual illustration of the high-level architecture of a JPEG Pleno box-based file format [6]

modalities under consideration, which require quality assessment paradigms going beyond those currently available.

Holographic data representation has a direct impact on all parts, eventually excluding Parts 2 and X, which are more directly related to light field and point cloud coding. Nonetheless, it is important to understand that the deployed box-based file format [6] is generic in a sense that the structural elements, that is, the box elements, are similar for all addressed modalities (see Figure 2). Evidently, it will incorporate some superboxes that contain modality specific content, namely the boxes that contain the effective compressed modality data, ie the codestreams. Nonetheless, other information such as color space definitions, and (calibration) metadata will be signaled by generic boxes valid for the different modalities. Because the various imaging modalities may be converted between each other—imagine for instance an imaging chain where a point cloud is converted to a hologram, which is subsequently rendered on a light field display [9]—the overall JPEG Pleno file format container will be utilized to contain successively, or at the end of the chain simultaneously, the different modality representations of the processed content. In summary, the JPEG Pleno file format can be considered as a Lego^{TM} box that allows for a (semi)flexible combination of its composing elements. Hence, though the coding technologies might be completely different, the file format can still guarantee a significant level of interoperability if desired.

Part Z will specify modality specific protocols for quality assessment. Nonetheless, it is not unimportant to mention that since all addressed modalities are plenoptic in nature these procedures might contain common elements or strategies in order to tackle the high-dimensionality of the quality assessment challenge. This observation is also supported by early experiments carried out by the JPEG committee and other actors in the field.

To better understand the standardization challenges for holographic images, below we first discuss the main use cases identified and present a resulting preliminary list of requirements.

2.2 | Holography related use cases

Despite multiple advantages, optical holography has had limited success in applications and markets until recently due to its most significant drawback: the analogue approach to recording and reconstructing complex amplitude information. This implies a time-consuming and cumbersome chemical process for hologram development and confines accessibility to recorded data. However, nowadays, digital holograms can be captured by digital cameras or created as computer generated holograms (CGHs). The obtained digital holograms can be easily reconstructed to viewable images using spatial light modulators (SLMs) or other numerical reconstruction methods. Due to advances in digital holography, holograms may now be widely used in many application domains such as in scientific research, medicine, and industry. The following sections introduce a few representative use cases of digital holography for which efficient coding is critical since large amounts of data must be stored or transmitted.

2.2.1 | Holographic microscopy

Holographic microscopy [10] records the light wavefront originating from an object instead of the projected image of the object recorded in common microscopy. The viewable image of the recorded hologram is created using a numerical reconstruction algorithm. Holographic microscopy supports a large depth of field, ie stacked wells can be recorded in one shot, and it enables the visualization of transmissive objects. This technique also facilitates cell refractive index tomography to facilitate the 3D reconstruction of cells. Examples of life science applications also include monitoring the viability of cell cultures in suspensions, automating multi-well plate screening devices to measure cell density and cell coverage of adherent cell cultures, and supporting simultaneous fluorescent and holographic cell imaging.

2.2.2 | Holographic interferometry

Holographic interferometry [11] is a full-field optical metrology tool that allows for a quantitative comparison of two states of an arbitrary scattering, reflective, or transmissive object subject to some change. It visually reveals temporal changes (eg, deformations, displacements, and modifications of the refractive index) without damage. The underlying principle is that incident light is reflected by the material at different angles before and after the change under consideration. Thus, holographic interferometry is widely used for non-destructive testing. It is also used in special digital cameras such as those in space and nuclear power station related applications, deep ocean exploration, and holographic endoscopes.

2.2.3 | Holographic display

Holographic displays can realize autostereoscopic rendering without vergence-accommodation conflict (VAC) [12]; this is because all the 3D depth cues perceived by humans in the real world are embedded in the holographic signal. The holographic display can be implemented in a variety of ways, including holographic TVs, table-top holographic displays, holographic projection systems, and holographic head-mounted displays (HMDs). The quality of holographic displays is associated with the so-called space-bandwidth product (SBP), which is a measure of the data capacity of electro-optical devices such as spatial light modulators (SLMs) [13,14]. In this context, overcoming the SBP constraints and limitations is regarded as a critical factor to realize a practical holographic display to reconstruct objects with both reasonable size and angular field of view (FOV). The pixel pitch of the top panels currently used in current TVs is close to 100 μm. For holographic displays, a pixel pitch of approximately 1 μm is required to provide a viewing angle of approximately 30° [15]. Therefore, a holographic display with the same size of a current TV would require approximately 10,000 (100 × 100) times more data, which means highly effective compression mechanisms are required. Consequently, it is to be expected that the first products to be released will have humble SBPs. Hence, early products are to be expected to first be in HMD and automotive windshield project system markets.

2.2.4 | Holographic printing

Holographic printing simultaneously offers the texture quality and spatial resolution of existing pictures and the 3D characteristics of holograms [16]. The latter enables depth cues and parallax to be provided, unlike in pictures. Holographic printing uses a laser to record captured discrete viewpoint images (holographic stereogram printing) or wavefront (wavefront printing) in holographic material. Holographic optical elements (HOEs) are used to perform the same functions as lenses, mirrors, gratings, diffusers, etc. and are a good example of holographic printing; they can also combine several functions together, which is not possible with conventional optical elements; hence, they hold the promise for extreme miniaturization of certain complex optical or digital image processing steps.

2.3 | Holography related requirements

In preparation for a Call for Proposals on holographic coding technology, the JPEG committee created a list of requirements, which must be fulfilled either in a compulsory or desired manner by candidate technologies for adoption in the standard specification. These requirements are the result of a thorough analysis of earlier discussed use cases. In parallel, additional requirements are imposed by the broader JPEG Pleno framework as well as other JPEG standards such as JPEG Systems [17].

Requirements range from the representation of complex amplitude data, over coding performance and codestream syntax, to application functionality. Table 1 provides a high-level overview of the main families of requirements and associated desires. At the time of writing, the requirements presented in this paper are still subject to intensive discussions. Hence, interested parties are welcome to further refine and complement the current list.

Moreover, the committee installs liaisons with other (standardization) organizations that are addressing the holography field with which use cases and requirements are exchanged. These liaisons are extremely important since they interface actors and organizations that are working on different components of an end-to-end holographic processing chain. By doing so, interoperability can be supported between different types of devices and content exchange between various applications can be facilitated. The JPEG standard is a good illustration of this: photographs taken with a camera or mobile phone can be shared across different platforms and applications without the need for conversion to different coding formats. Moreover, the associated file format allows for additional information about ICC color profile, EXIF metadata (camera settings, GPS location, photographer), privacy conditions, etc. to be signaled. In the context of JPEG Pleno, for example, a liaison was made with IEC TC 110, which has standardization activities in the field of electronic display devices, including which holographic displays [18].

3 | STATUS OF COMPRESSION TECHNOLOGY FOR HOLOGRAPHY

3.1 | Data representations

Holography enables to record and then reproduce both the amplitude and phase of the light wave scattered by a given scene. A fundamental problem in digital holography is therefore to find a suitable representation of this light wave (called object wave) that can be efficiently encoded and transmitted to the receiver. Two encoding data formats are commonly used: real-valued and complex-valued representations.

3.1.1 | Real-valued representations

Since current commercially available holographic displays based on spatial light modulators are only able to plot functions with real and positive values, holograms are often encoded using real-valued representations.

Two types of holograms can be obtained in this way: amplitude holograms and phase holograms. *Amplitude holograms* are only able to modulate the amplitude of the incident reference light wave. They are obtained either optically using a charge-coupled device (CCD) connected to a computer or numerically by simulating the phenomenon of interference occurring during the optical recording process.

If we call O and R the complex-valued object and reference waves in the hologram plane, respectively, the optically or numerically obtained amplitude hologram is given by

TABLE 1 Families of requirements under consideration for JPEG Pleno Holography.

Family	Requirements	Specification
Representation	Complex amplitude representations	Adopt an as small as sufficient number of representation models: amplitude-phase,real-imaginary, shifted-difference representation, or refractive index
	Large space-bandwidth product (SPB)	Enable large angular FoVs and displays by providing large spatial and spectral resolution ranges
	Color reproducibility	Allow for efficient signalling of spectral components, from binary to high dynamic range color definition, wide color gamut, XYZ color space, ICC profiles, transparency, and opacity
	Half/full parallax	Enable signalling and selection of both half and full parallax support
Coding performance and codestream syntax	Compression efficiency	Provide the highest possible decoding quality given a rate constraint
	Lossless and near-lossless coding	Facilitate respectively a perfect reconstruction of the raw input data after decoding or a high-quality reconstruction that is perceptually or quantitatively very close to the raw input data
	Perceptual quality control	Incorporate coding tools that exploit properties of the human visual system to reduce bitrate requirements
	Random access	Provide efficient methods to allow random or partial access to subsets of the complete compressed image data (eg parts of an hologram, or selected viewing angles) with fine granularity
	Scalability	Facilitate the extraction of different levels of quality (SNR), spatial resolution, depth resolution, temporal resolution, spectral resolution, number of viewing angles, and angular FoV from the codestream
	Ease of editing and manipulation	Allow for efficient change of depth of field or viewpoint, refocusing, relighting, navigation, rotation, and enhanced analysis of objects without necessary transcoding of content
	Error resilience	Protect against bit errors and packet losses for a large set of networks and storage devices
Algorithmic complexity	Low computational and memory complexity	Keep complexity within reasonable bounds when accounting for near-future computing devices
	Latency and real-time behavior	Provide minimal latency so as not to jeopardize real-time applications
	Parallel and distributed processing	Facilitate efficient implementations on GPU and multi-core architectures
	Hierarchical data processing	Allow for staged processing to reduce the strain on signalling channels in the display
Functionality	Decoupled capture and display	Incorporate signalling syntax or provide a mechanism to describe capturing and/or rendering conditions in order to transform content from capturing reference to rendering reference in the processing pipeline
	Display specific processing	Allow for information signalling necessary for display specific processing steps
	Controllable delay	Allow for control of the coding tool configuration such that the delay of the coding process can be kept within maximum bounds
	Additional metadata signalling	Enable signalling capture parameters, calibration data (eg geometrical setup), image sensor (CCD/CMOS) information, microscope configuration, spectral channel information, fluorescence metadata information, and information about additional processing steps
	Privacy and security	Provide compliance with JPEG Privacy and Security framework [19]
Compatibility	JPEG backward and forward compatibility	It is desired that any device implementing the new standard can also interpret all data compliant with the old version of the standard and vice versa
	JPEG Systems compatibility	The systems elements must comply with the relevant JPEG Systems specification

$$H = (O+R)(O+R)^* = |O|^2 + |R|^2 + 2\Re\{OR^*\}, \qquad (1)$$

where C^*, $|C|$, and $\Re\{C\}$ are respectively the conjugate, amplitude and real parts of complex number C.

In this equation, the first and second terms are the intensities of the object and reference waves, respectively. During the hologram reconstruction, these components are responsible for the zero diffraction order, which is an unwanted artefact that may overlap with the reconstructed object wave.

The third term is the interference pattern between the object and reference waves. While this component enables the reproduction of the object wave during hologram reconstruction, it is also responsible for the twin image artefact, which produces a pseudoscopic image of the scene. If the hologram is numerically computed, the first two terms can be omitted from the representation, yielding the so-called "bipolar intensity" [20], given by

$$H = 2\Re\{OR^*\}. \tag{2}$$

This representation presents the advantage of not including the zero diffraction order artefact during hologram reconstruction.

Holograms that modulate the phase of the reference wave are called *phase holograms or kinoforms*. Phase holograms have better diffraction efficiency than amplitude holograms because they do not modulate the amplitude of the incident reference wave. However, since optical sensing devices cannot record the phase of a light wave, these holograms must be computed using time-consuming phase retrieval methods such as the Gerchberg–Saxton algorithm [21].

Real-valued holograms present the advantage of encoding only half the data required to represent the complex object wave in the hologram plane. However, since they only modulate the amplitude or the phase of the reference light wave, real-valued holograms cannot faithfully replicate the object light wave.

3.1.2 | Complex-valued representations

To accurately reproduce the scene without any artefact and meet the representation requirements of Table 1, holograms should modulate both the amplitude and phase of the reference light wave. To this end, they must be encoded using complex-valued representations.

Complex-valued holograms can be computed by simulating the propagation of light scattered by the scene toward the hologram plane. They can also be acquired optically using phase-shifting holography [22,23]. In the latter case, a set of three interference patterns are optically recorded using a phase-shifted reference beam retarded by $\pi/2$ at each step, such that

$$H_0 = |O|^2 + |R|^2 + OR^* + O^*R, \tag{3}$$

$$H_{\pi/2} = |O|^2 + |R|^2 + jOR^* - jO^*R, \tag{4}$$

$$H_\pi = |O|^2 + |R|^2 - OR^* - O^*R. \tag{5}$$

These patterns are then combined to extract the object wave O, given by

$$O = \frac{(1+j)(H_0 - H_{\pi/2}) + (j-1)(H_{\pi/2} - H_\pi)}{4R^*}. \tag{6}$$

Regardless of the acquisition process used, complex-valued holograms can be encoded using amplitude-phase or real-imaginary representations. Figures 3 and 4 give the amplitude-phase and real-imaginary representations of hologram *Dices1080p* selected from the b<>com database.

In the *amplitude-phase representation*, O is expressed using a *polar coordinates system* such that

$$O = |O| \exp(j\phi(O)), \tag{7}$$

where $|O|$ is the amplitude of the object wave and $\varphi(O)$ is its phase, which is defined between 0 and 2π. By contrast, in the *real-imaginary representation*, O is expressed using a *Cartesian coordinates* system such that

$$O = \Re\{O\} + j\Im\{O\}, \tag{8}$$

where $\Re\{O\}$ and $\Im\{O\}$ are the real and imaginary parts of the object wave, respectively.

In the case of phase-shifted holograms, two other representation formats can also be used. The first one is to directly encode the set of interference patterns H_0, $H_{\pi/2}$, and H_π. However, this format implies the encoding of three sets of data, whereas only two are needed when using the amplitude-phase and real-imaginary representations. Another way is to use the *shifted distance*

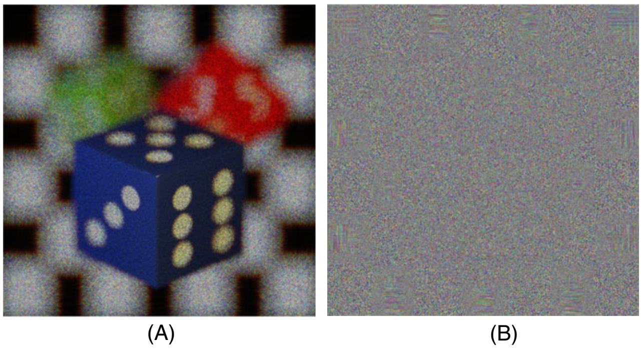
(A) (B)

FIGURE 3 Amplitude-phase representation of hologram *Dices1080p*, selected from the b<>com database: (A) Amplitude and (B) phase.

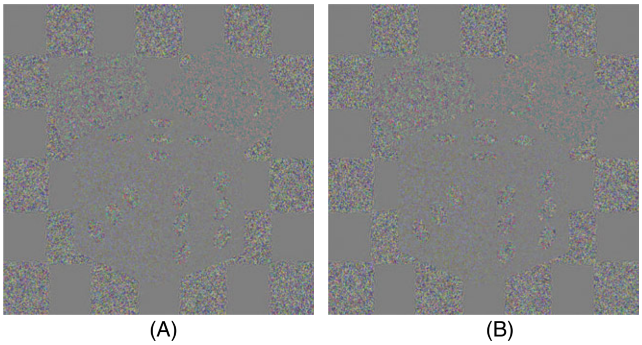
(A) (B)

FIGURE 4 Real-imaginary representation of hologram *Dices1080p*, selected from the b<>com database: (A) Real part and (B) imaginary part.

representation, defined by

$$D_0 = H_0 - H_{\pi/2}, \tag{9}$$

$$D_1 = H_{\pi/2} - H_{\pi}. \tag{10}$$

3.2 | Coding of holograms

3.2.1 | Positioning the problem

As explained in the previous section, holograms have either a real interference pattern or a complex representation of the light wavefield traversing a given surface in space (generally a planar surface). The compression strategies rely on the fundamental local meaning of this pattern as compared to the scene it represents.

It is thus legitimate to wonder why holograms should be encoded when they completely scramble information that would otherwise be a better candidate for compression: 3D or multi-view data exhibit high spatial regularity and their temporal changes are prone to intuitive prediction. Although 3D, multi-view, and 2D + Z coding techniques are ongoing research works and are always improving, they rely on stronger grounds than holographic pattern compression, which in essence is non-local. Since a scene can be represented by synthetic 3D, multi-view, or 2D + Z data, one would assume that encoders suited to these representations would be efficiently run before transmission, and that the hologram could be computed from this decoded 3D data on the client side.

When envisioning a fully interoperable framework for creating and transmitting holograms with data originating from various sources and displayed on heterogeneous terminals, this 3D pre-encoding strategy cannot be considered as a general framework for at least two reasons. The first one is that the 3D information of the scene is not always available; although holograms are often generated from synthetic or 2D + Z data, they may be optically acquired without any link to spatial data. Even if computer-generated, one may have to transmit a hologram without any information on the original 3D scene.

The second reason is that in this paradigm, *the terminal must perform the conversion from the spatial representation to the hologram pattern*, in addition to decoding the former. Although such generation methods have recently been considerably improved, at the time of writing, they are still *complex algorithms that require huge processing power* to run in real-time. It is obvious that not every terminal is able to carry out this task, which must be dedicated to a powerful module on the server side.

While hologram compression thus seems unavoidable, it can be assumed that the efficiency of a coding method depends on its capability to exploit the underlying spatial structure of the scene. Hence, in the remainder of the section, we review the various approaches and corresponding significant works from the most content-unaware methods, and we then consider ones that aim to extract 3D visualization features of the hologram to improve its coding efficiency, highlighting trends for future research.

Each surface element of a hologram intrinsically gathers the contributions of all the points emitting light within the recorded scene. The 3D information of the encoded scene is then scrambled into the holographic pattern. From there, *two fundamental obstacles* for compression can be observed. The first one is the *huge amount of data* captured in nature by the hologram; capturing the light emitted from a scene and traversing a surface is equivalent to providing a very dense distribution of perspectives of this scene, that is, it can be related to super multi-view data compression, with several thousands of views to encode [24]. The second obstacle is the *non-local nature of the data*, which prevents the straightforward extraction of redundancies between similar scenes; a small change occurring in the scene might translate into a completely different pattern on the hologram plane. Hence, temporal prediction is a difficult problem to solve when dealing with animated holograms and holographic video coding.

3.2.2 | Early attempts: Holograms as 2D pictures

In [25], Naughton et al. apply lossless coding techniques such as LZ77, LZW, and Huffman encoding to holograms generated by the phase-shifting interferometry method. Xing et al. [26] investigated the effects of quantization applied to different types of holographic representation. In particular, holograms generated by the phase-shifting digital holography method are tested, and the compression is performed by scalar (uniform and adaptive) quantization and by vector quantization, using the Linde–Buzo–Gray algorithm. A comparison of scalar vs vector quantization is provided by Cheremkhin et al. in [27].

These methods operate on the raw data and do not include any transform. Some authors have investigated the use of existing standard compression tools on the 2D representation of holograms. In [28] by Blinder et al., compression tests were carried out on holograms relating to the field of microscopy acquired by an off-axis technique using JPEG 2000 as a basis. Since a non-negligible quantity of information is

Note that coding in the hologram and object plane both come with their advantages and disadvantages. Object plane coding has the interesting feature that for semi-flat scenes all content is reasonably in focus, and hence classical 2D compression engines can be used. Unfortunately, this requires a backward light propagation step before encoding and a forward propagation step before rendering, increasing the computational complexity. It also fails in handling deep scenes. Hologram plane coding does not have these drawbacks, but current technologies fail to produce reasonable rate-distortion performance for scenes with a large SBP [15].

contained at high frequencies in off-axis holography, the decomposition mode of the codec input is modified (using Part 2 of the JPEG 2000 standard, which allows for the decomposition structures to be modified) to exceed the maximum limit of three decompositions of the high pass bands imposed by the JPEG 2000 standard. In this way it is possible to obtain a *full packet* decomposition structure.

In addition to encoding utilizing image coding standards (JPEG and JPEG 2000), Peixeiro et al. [29] performed compression tests with video standards (H.264/AVC and H.265/HEVC) on computer-generated holograms of grayscale virtual objects. The authors reported the compression performance of these codecs both before and after the hologram projection using different types of holographic data representation. Their tests show that H.265/HEVC provides the best rate-distortion performance. It is therefore proposed to extend this codec with rate-distortion optimized transforms that take into account the directionality of the input data. To achieve this aim, a set of residues are obtained, encoding some *training* holograms with H.265/HEVC. Subsequently, from these residues, transforms optimized with respect to them are designed.

3.2.3 | Adapting classical signal processing: Wavelet methods

Starting from the assumption that holographic data has different characteristics compared to traditional images, other authors have proposed alternative wavelet transforms, or at least adapted the classical settings to fit the characteristics of holographic data. Short et al. [30] and Cheremkhin et al. [31] compared various wavelet schemes and corresponding parameters in a search for the most suited scheme within the library of available classical wavelets, providing a first step toward adaptation to the content nature. Bang et al. [32] used a dual wavelet/bandelet transform to track the direction of the fringes. Blinder et al. [33] deployed a *directional adaptive* DWT (DA-DWT) to better align the transform bases with the specific directional characteristics of the fringe patterns in holographic data. A vector lifting scheme to design wavelets specially dedicated to hologram compression was proposed by Xing et al. in [34].

3.2.4 | Towards content-aware coding

While these methods, which are applied on the data in the hologram acquisition plane, aim to account for the specificities of holographic data, they do not exploit the 3D meaning of the local frequencies of the signal. It makes sense to assume that emerging efficient coding approaches will require this property. In addition to better extracting the relevant information, understanding the spatial semantics of the hologram could lead to interesting functionalities, such as graceful degradation, hologram editing or directional scalability. They are also likely suited to meaningful temporal prediction.

Although they do not yet provide superior compression results, some works have been proposed in this direction. In [35], Onural et al. made a preliminary intuitive link between the depth parameter in the Fresnel transform and the scaling parameter in the mother wavelet function. This idea was later exploited by Liebling et al. [36], leading to *Fresnelets*, which are wavelet-like functions constructed by Fresnel-transforming B-spline wavelets. The resulting basis functions allow the data with respect to the scene depth to be analyzed, and have been encoded with SPIHT [37]. Bernardo et al. [38] studied the impact of encoding the field at different depths. In particular, in the case of a single object, the benefit of performing coding in the reconstruction plane, ie object plane is discussed [39].

Lee et al. [40] used H.264/AVC to encode the numerical reconstructions of sub-holograms corresponding to specific viewing angles. Extending this approach, directional scalability was investigated by Viswanathan et al. [41] and El Rhammad et al. [42,43] using Gabor/Morlet wavelet dictionaries and a matching pursuit approach, providing a practical tool actually exhibiting the duality between light rays and local spatial frequencies.

A solution that addresses the problematic coding of deep scenes was recently proposed by Blinder et al. [44]. They explored an adaptive transform approach by defining a piece-wise propagation operator over non-planar surfaces based on linear canonical transforms. This work introduced a new coding paradigm.

The search for efficient hologram coding will most likely require further consideration of the characteristics of the hologram to extract the most essential information for 3D visualization. The requirements in Table 1 provide a guideline for allowing practical usage of such encoding; indeed, the emerging bitstream format should meet the requirements of the *Coding* row, which are generally well addressed by all listed methods, though with varying success as it concerns their rate-distortion performance. However, satisfying the *bitstream and codestream syntax* requirements implies reliance on an advanced coding solution allowing to gracefully extract relevant parts of the hologram data so that scalability, editing, and other manipulations can be part of the provided functionality.

4 | QUALITY EVALUATION

4.1 | Collection of test data

Although there is a growing interest in holographic information, there is still a limited amount of data available. The JPEG Pleno standardization effort has been gathering holographic data that is made available for research purposes. The JPEG Pleno databases have collected a significant number of digital holographic data. This data is becoming the true benchmarking set used nowadays. Currently, the main databases are as follows:

- **Interfere database** [45] Consist of two sets of computer generated holograms, which may be one of the most important applications of holography. This database has two sets of computed generated holograms: an original one and a more recent one that enlarges the diversity (represented in Figures 5 and 6 respectively).
- **b<>com holographic database** [46,47] This database is composed of colored computer generated holograms, calculated from synthetic 3D models or multiview-plus-depth data (Figure 7). Some of them were computed from 3D videos of real-existing scenes. Several bit depths, resolutions, and pixel pitches are offered, enabling a wide range of testing conditions.
- **EmergImg-HoloGrail database** [38,48] This database has several holograms obtained with a Mach-Zehnder interferometer setup [38]. It is one of the larger databases

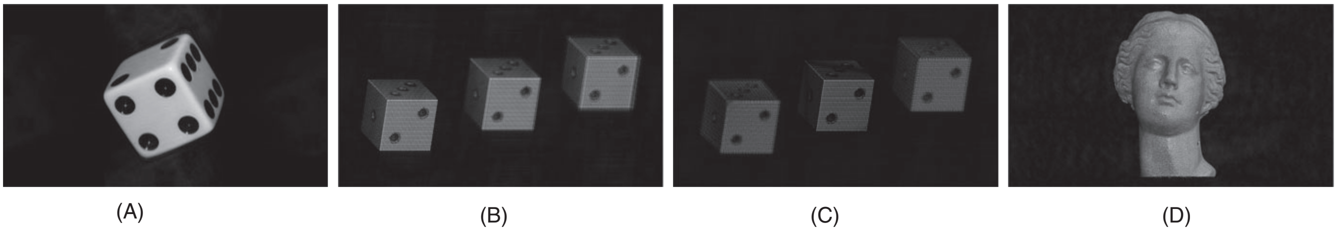
(A) (B) (C) (D)

FIGURE 5 Synthetic holograms selected from Interfere-I: (A) 2D dice, (B) 2Dmulti, (C) 3Dmulti, and (D) 3Dvenus

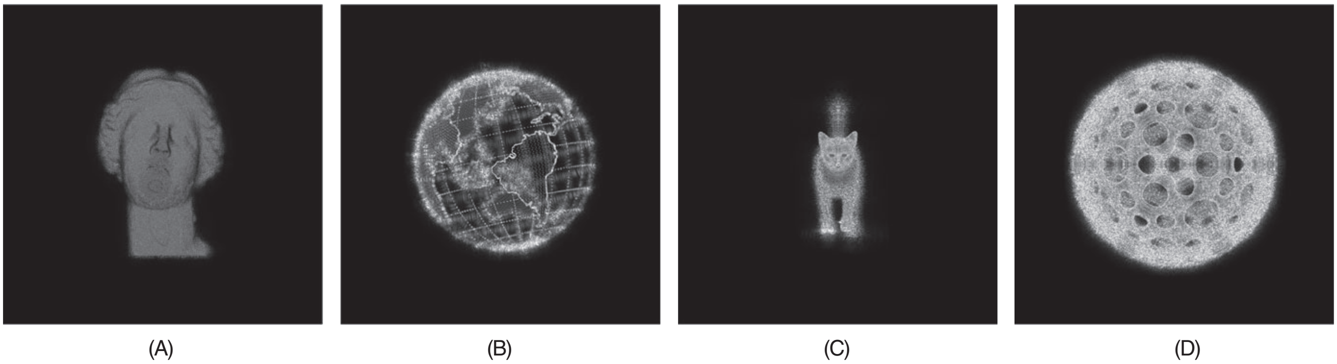
(A) (B) (C) (D)

FIGURE 6 Synthetic holograms selected from Interfere-II: (A) Venus8KS, (B) Earth 8KS, (C) Cat8KS, and (D) Ball8KS.

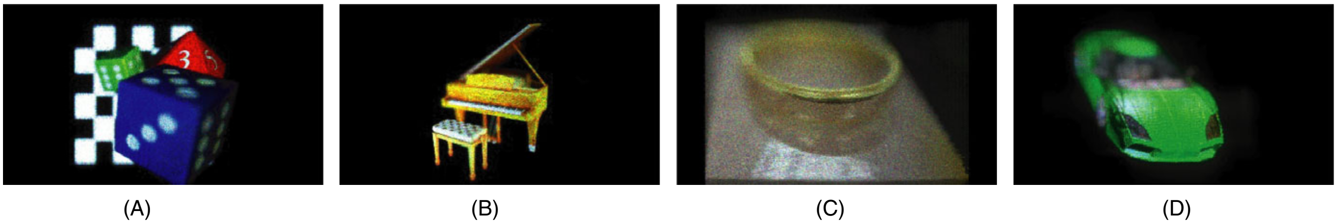
(A) (B) (C) (D)

FIGURE 7 Numerical reconstructions of synthetic holograms selected from the b<>com database: (A) Dices8k, (B) Piano8k, (C) Ring8k, and (D) Specularcar8k of acquired holograms. It initially included holograms of two chess pieces, a *Horse* and a *King*, a dice *Cube*, and a sequence of 54 images of a rotating *Car* (Figure 8). Recently, another four holograms have been added, two of them including multiple objects (Figure 9).

Finally, it is important to gain access to a large database of holographic microscopy. Although some data are available for the research community, currently no large database has been identified within JPEG Pleno, and holographic microscopy data is restricted to a few samples. However, this is one of the most important applications of digital holography, and the market offers several holographic microscopes able to acquire this specific type data.

4.2 | Measuring fidelity and assessing perceived quality

4.2.1 | Visual quality metrics

Notwithstanding the vast amount of research invested in image quality metrics, few efforts have been spent on developing advanced metrics for holographic content. This is evidently not surprising since, until recently, few researches have targeted the compression of holographic data. Most image quality related work was targets topics such as speckle noise reduction, improvement of the phase component for phase-only SLM-based rendering, and increasing the quality of the data for quantitative measurements in the context of interferometry, to give a some examples. In most of these cases, using simple image quality metrics such as maximum absolute error (MAE), mean-squared error (MSE), peak signal-to-noise error (PSNR), structural similarity index measure (SSIM), or speckle noise metrics suffice.

Unfortunately, these metrics only provide indications about maximum differences or global energy deviations between the compared holograms. These metrics measure the signal fidelity, providing a clear physical meaning and understanding, but a poor correlation with the visual quality as perceived by human observers [49]. Moreover, the fact that we handle interferometric complex amplitude data further complicates the problem. Depending on the nature of the representation, for example, real-imaginary or amplitude-phase, their application will be different and measurements can even be erroneous if not well taken care of. For example, phase wrapping might result in large error measurements, while the effective errors might be extremely small. Overall, applying these metrics on an amplitude-

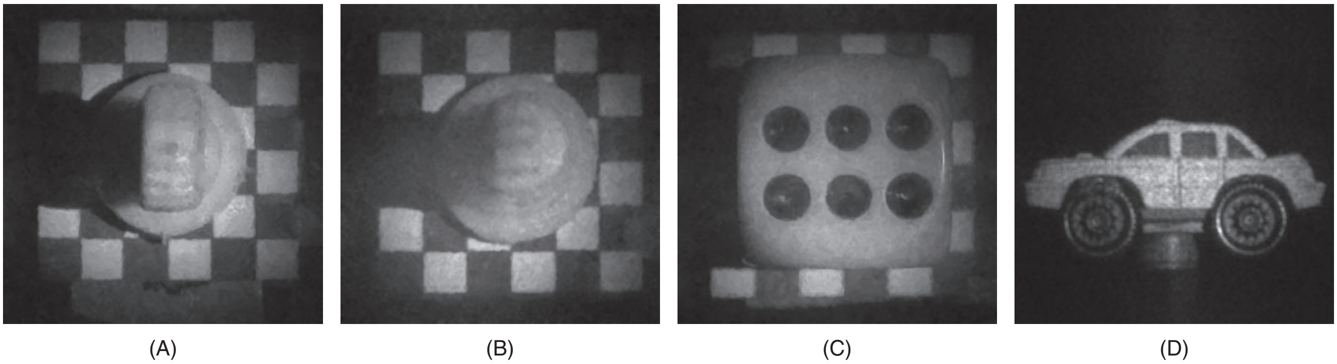
(A) (B) (C) (D)

FIGURE 8 Experimentally acquired holograms from EmergImg-HoloGrail-v1: (A) Horse, (B) King, (C) Cube, and (D) Car2575

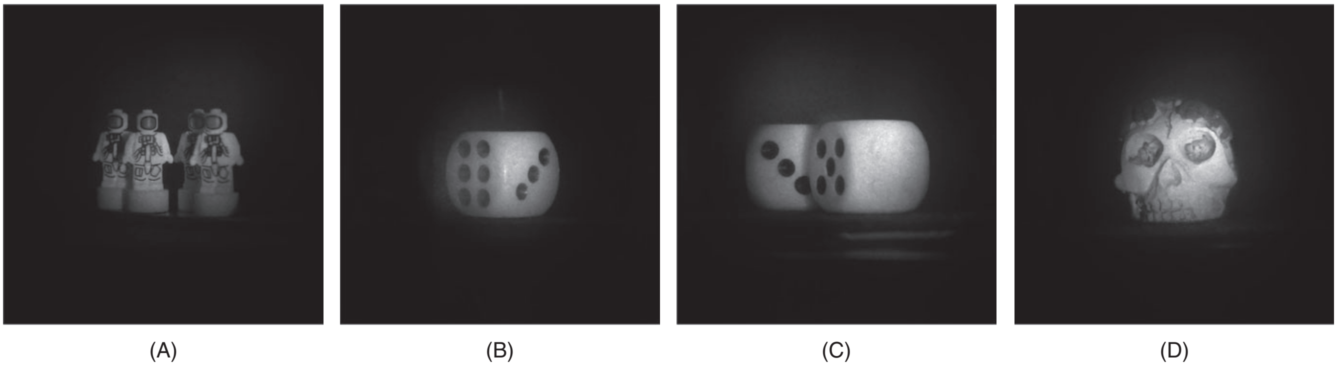
(A) (B) (C) (D)

FIGURE 9 Experimentally acquired holograms from EmergImg-HoloGrail-v2: (A) Astronaut, (B) Dice1, (C) Dice 2, and (D) Skull.

phase representation was found to deliver less accurate results compared to deploying them on Cartesian, that is, real-imagery representations [38].

Ahar et al. [50] recently presented a versatile similarity measure that attempts to resolve this caveat by proposing a multifactor measure (considering the factors accounting for amplitude, phase and sign differences) while ’annealing’ incidental phase wraps. Moreover, also a sparseness significance ranking measure (SSRM) [51] was proposed that is based on sparse coding and a ranking system for the magnitudes of the spatial frequency coefficients. This technique was shown to also be more effective than PSNR or SSIM on holographic data [52]. However, the latter two image fidelity measures are a humble step in the direction of developing more perceptually relevant image quality metrics; so far, no solutions have been presented for perceptual quality metrics suitable for holographic data.

Nonetheless, it is not the core business of the JPEG committee to develop quality metrics. Instead, it is interested in determining trustable measurement strategies and identifying metrics for evaluating coding technologies proposed for future standardization efforts. The lack of suitable—and generally accepted—public test data is one of the key factors in this context. Hence, the committee has also made an effort to collect and consensually evaluate the suitability of the selected data, as outlined in Section 4.1. Part of this effort relates to the next section: how to setup subjective quality experiments to collect perceptual scores for holographic content.

4.2.2 | Subjective assessment methodologies

Since visual quality metrics (both signal fidelity and perceptual quality measures) still do not provide an accurate prediction of the perceived visual quality, particularly for holograpic and plenoptic modalities in general, subjective quality assessment experiments must be performed.

JPEG has a long tradition in setting up such experiments as it is an obligatory component in the evaluation and testing process of new image coding standards. Depending on the nature of the content to be tested and growing insights, various test procedures have been deployed for different standardization projects, for example:

- JPEG 2000—Ranking test based on printed 300 dpi, 24-bit photographs of pictures compressed with JPEG and JPEG 2000 [53];
- JPEG XR—Double stimulus continuous quality scale (DSCQS) method, with side-by-side comparison and a continuous quality scale from 0 to 100 [54];
- JPEG XT—Double stimulus impairment scale (DSIS) with side-by-side comparison on a 4000 nits SIM2 HDR monitor and using a discrete quality scale with five impairment levels [55];
- JPEG XS—Flicker test for near-lossless encoded data on a 4K UHD, 10-bit colour depth display (Eizo CG318-4k) screen, with a ternary choice and in accordance with AIC Part 2 (ISO/IEC 29170-2) specifications [56] [57];
- JPEG Pleno Light Field Coding—Double stimulus comparison scale (DSCS) methodology with side-by-side rendering of the light field as a pseudo video sequence and using a discrete quality scale ranging from −3 to 3 [58]

In particular, plenoptic modalities pose additional challenges in terms of subjective quality assessment since the evaluation should target to the widest extend possible the full dimensionality of the representation to the widest extend possible. Moreover, this assessment process should preferably also account for the typical content consumption patterns, for example, movement patterns of users in front of plenoptic displays or typical content browsing behavior. For holographic content, an additional problem surfaces. At the time of writing this paper, no high-end holographic displays are available; only resolution and angular FoV limited experimental setups are possible. Looking at the current state-of-the-art of display technology, we might expect the first holographic display products to be in HMD and low-resolution projection system markets. These systems are already available in lab environments and hence, modeling experiments can be set-up that attempt to assess the relationship between numerically reconstructed holograms rendered on classic 2D, (auto)stereoscopic displays or in the best case, light field displays [59,15]. However, a thorough validation of this approach has not yet been performed. Hence, before launching a standardization process addressing this use case, reliable quality assessment procedures and strategies must be available in order to take meaningful decisions throughout the standardization process in terms of selecting the most appropriate coding technologies. Evidently, this will be even more relevant for high-SBP displays.

5 | NEXT STEPS

When evaluating the potential launch of a new standardization effort, the identification and definition of appropriate use cases and associated requirements is one of the first actions taken for a standard development. In addition, the committee collects evidence with respect to market needs and presence of candidate technological solutions. Currently, the committee has collected an initial set of use cases and requirements [1,8] and is probing the involved holographic community to receive further input to further refine and expand the collection. In addition, JPEG experts are continuously searching for evidence of suitable coding technology and identifying potential contributors.

However, this process also requires an appropriate protocol for quality evaluation that accounts for the use cases and requirements. This protocol is an important part of the common test conditions. Currently, a major effort is invested in this aspect. Therefore, the following items must be defined:

- An appropriate test data set that is representative for the addressed use cases and meets the defined requirements or at least a subset of them;
- A subjective evaluation procedure that allows for the evaluation of different compression technologies;
- A set of objective metrics that provide an acceptable representation of the subjective evaluation results.

A subjective evaluation is not always easy to define, especially in cases where new variables to consider exist, and consequently there are additional degrees of freedom compared to traditional 2D imaging and visualization. In the current case, the evaluation must provide some level of importance to the level of 3D information or parallax between other properties, which do not exist in typical 2D imaging. Moreover, holographic data quality is often highly influenced by the speckle noise, which has an influence on the subjective notion of quality. Hence, the definition of an appropriate methodology must be carefully studied and defined.

Furthermore, the definition of appropriate objective metrics is also not straightforward. Once again, they must be the most representative of subjective evaluation and consider the specificity of the holographic data and associated 3D information. Moreover, they must be versatile and reliable to deal with the distortions produced by different compression technologies.

6 | CONCLUSIONS

From the modalities addressed by JPEG Pleno, holography most likely depicts the largest diversity in addressed use cases and associated technologies. Consequently, coding technology diversity will also be required to efficiently address the varying nature in terms of desired representation, SBP and spectral footprint of the holographic signal to be encoded. Moreover, the maturity of the markets across these use cases widely varies. Holographic microscopy and interferometry have found many applications in biomedical applications, industrial measurements, etc. On the other hand, holographic display and printing have not reached the commercial markets yet and can be considered to be in a research phase. It is fair to say that the maturity of the associated coding technologies has evolved on par for those use cases, with huge challenges remaining for holographic displays.

Hence, in coordination with the stakeholders, the committee will define a standard implementation roadmap to assure timely interoperability in the domain. We like to conclude this paper by inviting interested parties to join this process. Recent information about JPEG Pleno and participation information can be obtained on the JPEG website [60] or by contacting the authors of this paper.

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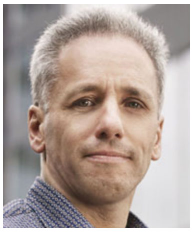
REFERENCES

1. ISO/IEC JTC1/SC29/WG1, *JPEG PLENO Abstract and Executive Summary*, WG1N6922, 68th JPEG Meeting, Sydney, AustraliaFebruary 2015, Feb 2015.
2. T. Ebrahimi et al., *JPEG Pleno: toward an efficient representation of visual reality*, IEEE Multimedia **23** (2016), no. 4, 14–20.
3. ISO/IEC JTC1/SC29/WG1, *JPEG Pleno Part 1—ISO/IEC 21794-1 WD2.0*, WG1N80009, 80th JPEG Meeting, Berlin, Germany, July 2018.
4. ISO/IEC JTC1/SC29/WG1, *JPEG Pleno Call for Proposals on Light Field Coding*, WG1N74014, 74th JPEG Meeting, Geneva, Switzerland, Jan. 2017.
5. ISO/IEC JTC1/SC29/WG1, *JPEG Pleno Light Field Coding Verification Model 1.0*, WG1N80028,80th JPEG Meeting, Berlin, Germany, July 2018.

6. ISO/IEC JTC1/SC29/WG1, *JPEG Pleno Part 2—ISO/IEC 21794-2 WD2.0*, WG1N81057, 81th JPEG Meeting, Vancouver, Canda, Oct 2018.
7. ISO/IEC JTC1/SC29/WG1, *JPEG Pleno Point Clouds—Use Cases and Requirements*, WG1N80018, 80th JPEG Meeting, Berlin, Germany, July 2018.
8. ISO/IEC JTC1/SC29/WG1, *JPEG Pleno Holography—Overview of Holography 2.0*, WG1N80042, 80th JPEG Meeting, Berlin, Germany, July 2018.
9. A. Symeonidou et al., Three-dimensional rendering of computer-generated holograms acquired from point-clouds on light field displays, *Applications of Digital Image Processing XXXIX*, vol. **9971**, SPIE, 2016, pp. 99710S.
10. M. K. Kim *Digital Holographic Microscopy: Principles, Techniques, and Applications*, Springer Series in Optical Sciences, New York, USA, (2011).
11. C. M. Vest, *Holographic interferometry*, John Wiley and Sons, New York, USA, 1979.
12. D. M. Hoffman et al., *Vergence-accommodation conflicts hinder visual performance and cause visual fatigue*, J. Vis. **8** (2008), no. 3, 33–33.
13. A. W. Lohmann et al., *Space-bandwidth product of optical signals and systems*, J. Opt. Soc. Am. A **13** (1996), no. 3, 470–473.
14. J. W. Goodman, *Introduction to Fourier optics*, Roberts & Company, Greenwood Village, CO, USA, 2004.
15. D. Blinder et al., *Signal processing challenges for digital holographic video display systems*, Signal Proces. Image Commun. **70** (2019), 114–130.
16. M. Yamaguchi, N. Ohyama, and T. Honda, *Holographic three-dimensional printer: new method*, Appl. Opt. **31** (1992), no. 2, 217–222.
17. ISO/IEC JTC1/SC29/WG1, *JPEG systems website*, 2018, Available at http://jpeg.org/jpegsystems (last accessed Sept. 2018).
18. IEC TC 110, *IEC TC 110 Website*, 2018, Available at https://www.iec.ch/dyn/www/f?p=103:7:0::::FSP_ORG_ID,FSP_LANG_ID:1313,25 (last accessed Nov. 2018).
19. F. Temmermans et al., *JPEG Privacy and Security framework for social networking and GLAM services*, EURASIP J. Image Video Process. **2017** (2017), 68: 1–9.
20. M. E. Lucente, *Interactive computation of holograms using a look-up table*, J. Electron. Imaging **2** (1993), no. 1, 28–34.
21. R. W. Gerchberg and O. Saxton, *A practical algorithm for the determination of the phase from image and diffraction plane pictures*, Optik **35** (1971), no. 2, 237–246.
22. I. Yamaguchi and T. Zhang, *Phase-shifting digital holography*, Opt. Lett. **22** (1997), no. 16, 1268–1270.
23. Y. Awatsuji et al., *Parallel three-step phase-shifting digital holography*, Appl. Opt. **45** (2006), no. 13, 2995–3002.
24. Z. Y. Alpaslan, H. S. El-Ghoroury, and P. Schelkens, Information processing challenges of full parallax light field displays, *SPIE Photonics Europe 2018, Optics, Photonics and Digital Technologies for Multimedia Applications*, vol. **10679**, SPIE, 2018.
25. T. J. Naughton et al., Compression of digital holograms for three-dimensional object recognition, *Algorithms and Systems for Optical Information Processing V*, vol. **4471**, International Society for Optics and Photonics, 2001, pp. 280–290.
26. Y. Xing, B. Pesquet-Popescu, and F. Dufaux, Comparative study of scalar and vector quantization on different phase-shifting digital holographic data representations, *3DTV-Conf.: True Vision-Capture, Transmission Display 3D Video (3DTVCON)*, Budapest, Hungary, July 2–4, 2014, pp. 1–4.
27. P. A. Cheremkhin and E. A. Kurbatova, *Numerical comparison of scalar and vector methods of digital hologram compression*, Proc. Holography, Diffractive Opt. Applicat. VII **10022** (2016), 1002227: 1–10.
28. D. Blinder et al., Wavelet coding of off-axis holographic images, *Applications of Digital Image Processing XXXVI*, *Proc. SPIE* **8856**, (2013), pp. 88561L: 1–2.
29. J. P. Peixeiro et al., *Holographic data coding: Benchmarking and extending HEVC with adapted transforms*, IEEE Trans. Multimedia, 20 (2018), no. 2, 282–297.
30. A. E. Shortt, T. J. Naughton, and B. Javidi, *Compression of digital holograms of three-dimensional objects using wavelets*, Opt. Express **14** (2006), no. 7, 2625–2630.
31. P. A. Cheremkhin and E. A. Kurbatova, Compression of digital holograms using 1-level wavelet transforms, thresholding and quantization of wavelet coefficients, *Digital Holography and Three-Dimensional Imaging* Jeju, Rep. of Korea, May 29 -June 1, 2017, pp. W2A.38: 1–3.
32. L. T. Bang et al., *Compression of digital hologram for three-dimensional object using Wavelet-Bandelets transform*, Opt. Express **19** (2011), no. 9, 8019–8031.
33. D. Blinder et al., *JPEG 2000-based compression of fringe patterns for digital holographic microscopy*, Opt. Eng. **53** (2014), no. 12, 123102: 1–13.
34. Y. Xing et al., *Adaptive nonseparable vector lifting scheme for digital holographic data compression*, Appl. Opt. **54** (2015), no. 1, A98–A109.
35. L. Onural, *Diffraction from a wavelet point of view*, Opt. Lett. **18** (1993), no. 11, 846–848.
36. M. Liebling, T. Blu, and M. Unser, *Fresnelets: new multiresolution wavelet bases for digital holography*, IEEE Trans. Image Process. **12** (2003), no. 1, 29–43.
37. E. Darakis and J. J. Soraghan, *Use of Fresnelets for phase-shifting digital hologram compression*, IEEE Trans. Image Process. **15** (2006), no. 12, 3804–3811.
38. M. V. Bernardo et al., *Holographic representation: hologram plane vs. object plane*, Signal Proces. Image Commun. **68** (2018), 193–206.
39. M. Bernardo, A. Pinheiro, and M. Pereira, Benchmarking coding standards for digital holography represented on the object plane, *Proc. SPIE 10679, Optics, Photonics, and Digital Technologies for Imaging Applications V, SPIE Photonics Europe*, SPIE, Apr. 2018, pp. 6–8.
40. D. H. Lee et al., Viewing angle dependent coding of digital holograms, Eur. *Signal Process. Conf.*, Barcelona, Spain, Aug. 2011, pp. 1367–1371.
41. K. Viswanathan, P. Gioia, and L. Morin, Wavelet compression of digital holograms: towards a view-dependent framework, *Applications of Digital Image Processing XXXVI*, vol. **8856**, International Society for Optics and Photonics, 2013, pp. 88561N.
42. A. El Rhammad et al., *Color digital hologram compression based on matching pursuit*, Appl. Opt. **57** (2018), no. 17, 4930–4942.
43. A. El Rhammad et al., View-dependent compression of digital hologram based on matching pursuit, *Optics, Photonics, and Digital Technologies for Imaging Applications V*, vol. **10679**, International Society for Optics and Photonics, May 2018, pp. 106790L.

44. D. Blinder et al., *Unitary transforms using time-frequency warping for digital holograms of deep scenes*, IEEE Trans. Comput. Imag. **4** (2018), no. 2, 206–218.
45. D. Blinder et al., Open access database for experimental validations of holographic compression engines, *Int. Quality Multimedia Experience (QoMEX)*, Pylos-Nestoras, Greece, May 26–29, 2015, pp. 1–6.
46. A. Gilles et al., *Hybrid approach for fast occlusion processing in computer-generated hologram calculation*, Appl. Opt. **55** (2016), no. 20, 5459–5470.
47. A. Gilles et al., Computer generated hologram from multiview-plus-depth data considering specular reflections, *IEEE Int. Conf. Multimedia Expo Workshops (ICMEW)*, Seattle, WA, USA, July 11–15, pp. 1–6.
48. M. V. Bernardo et al., A digital hologram compression scheme for representation on the object plane, *Proc. SPIE 10752*, Applications of Digital Image Processing XLI, SPIE Optics + Photonics, SPIE, Aug. 2018.
49. W. Lin and C.-C. Jay Kuo, *Perceptual visual quality metrics: a survey*, J. Vis. Commun. Image Represent. **22** (2011), no. 4, 297–312.
50. A. Ahar et al., A new similarity measure for complex valued data, *Digital Holography Three-Dimensional Imaging*, Jeju, Rep. of Korea, May 29–June 1 2017, pp. Tu1A.6: 1–3.
51. A. Ahar, A. Barri, and P. Schelkens, *From sparse coding significance to perceptual quality: a new approach for image quality assessment*, IEEE Trans. Image Process. **27** (2018), no. 2, 879–893.
52. A. Ahar et al., Performance evaluation of sparseness significance ranking measure (SSRM) on holographic content, *Applicat. Lasers Sensing Free Space Commun*, Orlando, FL, USA, 25–28. 2018, pp. Tu4A. 10: 1–2.
53. ISO/IEC JTC1/SC29/WG1, *Visual evaluation of JPEG 2000 color image compression performance*, WG1N1583, 19th JPEG Meeting, Tokyo, Japan, 2001.
54. F. De Simone et al., Subjective evaluation of JPEG XR image compression, *Applications of Digital Image Processing XXXII*, vol. **7443**, International Society for Optics and Photonics, 2009, pp. 74430L.
55. A. Artusi et al., *Overview and evaluation of the JPEG XT HDR image compression standard*, J. Real-Time Image Proc. (2015), 1–16.
56. *ISO/IEC 29170-2:2015 Information technology—Advanced image coding and evaluation—Part 2: Evaluation procedure for nearly lossless coding*, Available at https://www.iso.org/standard/66094.html (last accessed June 16, 2018).
57. A. Willème et al., Overview of the JPEG XS core coding system subjective evaluations, *SPIE Optics + Photonics 2018, Applications of Digital Image Processing XLI*, vol. **10752**, SPIE, San Diego, CA, USA, 2018.
58. I. Viola and T. Ebrahimi, Quality assessment of compression solutions for ICIP 2017 Grand Challenge on light field image coding, *Int. Conf. Multimedia Expo Workshops*, San Diego, CA, USA, July 23–27, 2018.
59. A. Symeonidou et al., Three-dimensional rendering of computer-generated holograms acquired from point-clouds on light field displays, *SPIE Optics + Photonics, Applications of Digital Image Processing XXXIX*, vol. **9971**, SPIE, 2016, pp. 99710S.
60. ISO/IEC JTC1/SC29/WG1, *JPEG website*, 2018, Available at http://jpeg.org (last accessed September 2018).

AUTHOR BIOGRAPHIES



Peter Schelkens holds a professorship with the Department of Electronics and Informatics, Vrije Universiteit Brussel, Belgium and is a Research Group Leader at imec, Belgium. In 2013, he received an EU ERC Consolidator Grant focusing on digital holography. He is the co-editor of the books The JPEG 2000 Suite (Wiley, 2009) and Optical and Digital Image Processing (Wiley, 2011). He is chair of the Coding, Test and Quality subgroup of the ISO/IEC JTC1/SC29/WG1 (JPEG) standardization committee and Associate Editor for the IEEE Transactions on Circuits and Systems for Video Technology, and Signal Processing: Image Communications.

Touradj Ebrahimi is a professor at the Swiss Federal Institute of Technology in Lausanne (EPFL), working in teaching and research in multimedia signal processing. He is also Convener of the JPEG standardization committee, which has produced a family of standards that have revolutionized the world of imaging. He was also an adjunct professor at NTNU and has founded two companies: Emitall SA which is a high-tech company active in the field of digital media innovations, and Emitall Surveillance, which is active in the field of intelligent video surveillance systems. He represents Switzerland as the head of its delegation to SC29 (the body that oversees MPEG and JPEG standardization committees), and he acted as the chairman of the SC29 Advisory Group on Management for many years until 2014.

Antonin Gilles received his MS in electronics and computer engineering and his PhD in signal and image processing from the National Institute of Applied Sciences, Rennes, France, in 2013 and 2016, respectively. He is now working as a researcher on Computer-Generated Holography at the Institute of Research and

Technology b<>com, Rennes, France. His main research interests include realistic full-color hologram synthesis, real-time hologram calculation and holographic data compression. He is involved in the ISO/IEC JTC1/SC29/WG1 (JPEG) standardization committee.

Patrick Gioia received his MS in mathematics and PhD in computer science from the University of Rennes, France, in 1997 and 2000, respectively. Since then he has been a Research Engineer at Orange Labs, working on 3D scalable coding based on wavelets. From 2000 to 2010 he has actively contributed to the MPEG-4 standardization of synthetic scene scalable streaming. He joined the Institute of Research and Technology b<>com in 2013, where he works on Computer Generated Holograms and Digital Hologram Coding.

Kwan-Jung Oh received his M.S. and Ph.D. degrees in Information and Communications Engineering from the Gwangju Institute of Science and Technology (GIST), Gwangju, Rep. of Korea, in 2005 and 2010, respectively. From 2010 to 2013, he was with the Samsung Advanced Institute of Technology (SAIT), where he was involved in standardization activities of 3D video coding. He joined the Electronics and Telecommunications Research Institute (ETRI), Daejeon, Rep. of Korea in 2013, where he is currently a Senior Researcher with the Broadcasting and Media Research Laboratory. His research interests include 3-D image and video coding, immersive media, and holography.

Fernando Pereira is an associate professor at the Instituto Superior Tecnico (University of Lisboa) and is heading the Multimedia Signal Processing group of the Instituto de Telecomunicac¸ões in Lisbon, Portugal. He is also the Requirements subgroup chair of the JPEG Standardization Committee. He is an IEEE, EURASIP and IET Fellow.

Cristian Perra is an assistant professor of Communications at the Department of Electrical and Electronic Engineering, University of Cagliari, Italy. He is a research associate at the Multimedia Communications Laboratory of CNIT (Consorzio Nazionale Interuniversitario per le Telecomunicazioni) in Cagliari, Italy. In 2003, he received his PhD in electronic engineering and computer science from the University of Cagliari. He is a member of the ISO/IEC JTC1/SC29/WG1 (JPEG) standardization committee. His main research interests include multimedia communications, image/video/point cloud/light field/holography signal processing, virtual reality and augmented reality applications, and quality of experience for multimedia communications.

Antonio M. G. Pinheiro is an assistant professor at U.B.I. (Universidade da Beira Interior), Covilhã, Portugal and a researcher at I.T. (Instituto de Telecomunicac¸ões), Portugal. He received his B.S. (Licenciatura) from I.S.T., Lisbon in 1988 and his Ph.D. in electronic systems engineering from the University of Essex in 2002. Currently, his research interests are on image processing, namely on for multimedia quality evaluation, emerging 3D imaging technologies, and medical image analysis. He is currently involved in the project EmergIMG, a Portuguese consortium on emerging image technologies, funded by the Portuguese Funding agency and H2020. He is a Portuguese delegate to the JPEG standardization committee, where he is currently the Communication Subgroup chair and is involved with the JPEG Pleno development.