A Roadmap Towards Holographic Television
From a Signal Processing Perspective

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\textbf{Abstract:} In recent years, the domain of plenoptic imaging has seen significant scientific and industrial evolutions. We present novel signal processing technologies addressing holographic imaging, ranging from capture to rendering of complex amplitude digital holograms.

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1. Introduction

Plenoptic imaging — for which holography is a key enabling modality — has experienced significant scientific and industrial evolutions. In this context, the ERC INTERFERE project has focused on the design of end-to-end signal processing solutions for holographic television systems. Such systems are envisioned to use heterogeneous signal sources, originating from light field sensors and camera arrays, point cloud scanners, time-of-flight (TOF) cameras or even holographic sensing devices (for miniature scenes) that are subsequently converted to a generic, sparse, holographic representation format, utilizing computer generated holography (CGH) techniques. From this holographic ‘information container’, a continuum of views can be extracted that serves as input for e.g. holographic head mounted display (HMD) devices or interactive holographic visualization tables.

How to efficiently capture, represent and transmit this holographic information are key questions. In the following section, we stance on a signal processing perspective and will outline the main research challenges pictured in the concept mind map in Figure 1. We address the problem as a whole and segment the signal processing pipeline from capture to visualization. As illustrated in Figure 2, the underlying representation of the plenoptic function is fundamental for signal processing and we establish bridges between the 4D ray-based light field intensities and the 2D wavefront-based holographic complex amplitudes representations.

2. Roadmap

Computer Generated Holography (CGH) It is to be expected that most of the source material in holographic vision chains will be captured by non-holographic devices and/or based on computer generated content. Efficient techniques are desired to convert this content to an holographic representation. One of the challenges will be to determine where in the system chain this conversion will take place: at postproduction, before broadcast or at the client side. The overall complexity of the involved algorithms, the efficiency of the representations deployed and the flexibility of the plenoptic container format, will be determining factors. From this perspective, the complexity of CGH algorithms should be reduced significantly and inputs from various sources should be supported. A technique recently proposed for point cloud sources includes a novel approach for occlusion culling with limited additional computation cost [1]. Performance tests demonstrated that for a full-parallax high-definition CGH, a speedup factor of more than 2,500 compared to the reference ray-tracing method can be achieved without hardware acceleration. The technique has been further improved to reduce speckle noise and to model bidirectional reflectance distribution functions (BRDF).

Source Coding As holograms exhibit signal properties that differ significantly from natural imagery, it stands to reason that alternative transforms need to be developed to effectively process and sparsify digital holograms. Traditional transforms such as Daubechies wavelets, Fresnelets, directional wavelet filters and various packet and multiscale algorithms are desirable tools in this context.
decompositions are interesting options and have been subject to many studies. A codec for static holograms delivering state of the art performance [2] has been proposed as a generic architecture suitable for the compression of many types of holograms. This framework has a JPEG 2000 codec at its core, and is extended with fully arbitrary wavelet decomposition styles and directional wavelet transforms. Significant improvements in coding performance have been reported for off-axis holography relative to the conventional JPEG 2000 standard, with Bjøntegaard delta-peak signal-to-noise ratio improvements ranging from 1.3 to 11.6 dB for lossy compression in the 0.125 to 2.00 bpp range and bit-rate reductions of up to 1.6 bpp for lossless compression [3].

The performance of such codecs can be further improved by designing fast transforms such as modulo wavelets [4] that are a new class of nonlinear wavelets that are defined to effectively process wrapped phase data. This transform can be combined with many phase unwrapping algorithms, resulting in speeds of factors up to 500. The source code is public and free. Currently, we have devised motion compensation techniques that allow us provide accurate predictions of 3D objects that undergo 3D translational and rotational motion, i.e. the 6 DOFs of rigid body motion.

**Quality Assessment** While designing holographic source codecs, it is of utmost importance to build a sound understanding of factors influencing the visual quality of the decoded content, how to integrate in the codec knowledge about the human visual system and to design subjective assessment procedures and quality metrics suitable for holographic content. We have developed alternative strategies to investigate the structural integrity of hologram data. Utilizing the holographic test data that was generated by our CGH algorithms, we subjectively assessed, deploying a double stimulus method on high-end 4K displays [5]. In a subsequent step, our holograms were converted into light fields and rendered on a Holografika HoloVizio 722RC display, with a field of view of 70° with 1 view per degree [6].

Sparse coding is known to be one of the main underlying strategies for image understanding by the human’s brain and seen the nature of holographic content. An alternative categorization of frequency components was proposed, where instead of considering frequency indices or HVS characteristics (e.g. visual masking, contrast sensitivity function), their importance for sparse coding, namely *sparseness significance* was considered for differentiation. We proposed a new characterization of structural information in the Fourier domain based on this idea [7]. After evaluating the behaviour of Fourier components of the distorted images in complex plane utilizing the notion of distortion vectors, we designed a novel perceptual quality predictor.

**JPEG Standardization** JPEG Pleno intends to provide a standard framework to facilitate capture, representation and exchange of omnidirectional, depth-enhanced, point cloud, light field, and holographic imaging modalities [8]. These standardization efforts are of particular importance to define the future tools in industry and for improved compression while providing advanced functionalities at the system level. JPEG Pleno also aims at supporting data

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**Fig. 1.** Connected cross-disciplinary problems have to be addressed in a synchronized framework for enabling content capture and generation, compression and transmission, and final display.
and metadata manipulation, editing, random access and interaction, protection of privacy and ownership rights as well as other security mechanisms. Recently also a JPEG Ad Hoc Group was established with the mandate of validating holographic test data sets and probe for evidence to launch a standardization activity in the context of JPEG Pleno. Very recently, a call for proposals for light field coding was published (https://jpeg.org/jpegpleno).

3. Conclusion
To make future holographic television a reality, stronger collaboration needs to be fostered between photonics and digital signal processing communities. While underlying hardware and software technologies are maturing as a pair, we need to start investing efforts in the end-to-end architectural aspects of such systems, which are on their turn again heavily impacting the design decisions related to the individual components. Symbiosis and mutual benefits are to be envisioned from standardization (cfr. JPEG Pleno) in the broader domain of plenoptic imaging.

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