Extending AV1 Codec to Enhance Quality in Phase Compression of Digital Holograms in Object and Hologram Planes

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***Abstract*—Holography is a 3D capturing and displaying system. Many formats have been suggested to store holographic images with the highest quality and minimum file size. Here, we suggest combining two AV1 codecs to make a secondary error image and use it in a linear regression block to compensate for the main AV1 compression error. Since the phase part is the most challenging part of holograms, the proposed method addresses the compression problem in phase. The obtained results reveal that the proposed method can outperform the state-of-the-art codecs in terms of PSNR and SSIM criteria. Besides, comparing BD-PSNR and BD-Rate results with usual AV1, confirms the proposed method has an average about 5.04dB, which is -22.1% better Object plane performance, and 4.57dB, which is -20.66% better in Holo plane performance, in terms of BDPSNR and BD-Rate, respectively.**

Keywords—Compression; digital holography; object plane; holo plane; phase compression

I. INTRODUCTION

Holography is a technique for capturing three-dimensional (3D) images and videos. Holography is first proposed to enhance the quality of electron microscopes that were expanding at that time. In the 1960s, optical holography was advanced considerably by the development of laser [1]. In the early 1990s, decent quality digital holograms were recorded, processed, and stored using a space light modulator (SLM), CCD camera, mathematical algorithms, and fast computers. Nowadays, digital holography is applied to a wide variety of purposes such as electron microscopes [2], interferometry [3, 4, 5], surface sensing [6], data storage, holographic projectors, virtual reality, optical tweezers [7], optical information security [7, 8], and 3D movies [9]. Holograms are computationally intensive, being more evident in video or live scenes. Thus, research about hologram codecs and compression algorithms is currently highly demanded [10]. With the growth of 3D display media on the Internet, 3D imaging technologies are expected to be one of the most exciting imaging areas soon. One of the main hurdles in this new industry is to devise hologram codecs that can use the available bandwidth and transfer 3D images optimally.

The existing 3D technologies based on the light field have limitations [11, 12]. In contrast, holography, considered an infinite light field, nominates as an alternative technology to the existing techniques [13]. However, there are numerous challenges to developing all aspects of the 3D holographic industry, including 3D display technology, recording equipment and cameras, noise removal from hologram images [14] and hologram broadcasting. Given the existing challenges, this study proposes a holographic compression based on AOMedia Video 1 (AV1) image compression. It significantly reduces the required bandwidth for holographic image broadcast without lowering the quality of holograms. Due to the high storage and bandwidth required for holographic images (about 10 Gbps), the proposed 3D compression method is highly desirable. It resolves one of the most significant limitations to the future of 3D imaging technology and helps broaden the 3D media field significantly. There are three traditional standards for displaying and recording holographic images [15, 16, 17]:

A. Intensity-based format

This standard directly extracts holographic images from three phase-shifted stored interferograms and directly uses the holographic equation. Here, three 2D (two-dimensional) datasets are required to store holograms. This format is not optimum for storage due to its high data requirements.

B. Phase-shifted format

In this case, the object is modelled as a complex object wave-field with two different signals in different phases. This format requires two 2D matrices to store holograms. Although this representation presents computational complexity in the coding and decoding step, it requires less information than the intensity-based standard.

C. Complex object wave-field format

In this format, the hologram is stored using complex numbers, represented in Cartesian or polar forms. Some studies report that the polar form is more robust and efficient, particularly in lossy codecs [18]. However, the loss of holograms phase part in compression is not considered independently in the literature, although holograms are critically sensitive to it.

This article intends to cover the research gap presented in complex object wave-field format. First, it is examined the efficiency of different compression methods on the holographic image phase part. Then, an efficient phase compression method on holographic images for both holo-plane and object-plane is proposed. The structure of this article is as follows. The next section provides a comprehensive overview of the holographic structure and related works. In Section 3, the proposed method is explained in detail. Next, the method is compared against the best counterparts in Section 4. Finally, Section 5 concludes the article.

II. Hologram Coding and Compression

Generally, 3D compression methods can be divided into four classes:

- Wavelet-based methods;
- Frequency domain methods such as DCT/FFT-methods and JPEG;
- Hybrid codecs such as HEVC, AV1, and VP9;
- Other codecs.

A. Wavelet-based Compression Methods

Wavelets offer excellent compression properties in signal and image [19, 20]. As a consequence, they are among the first candidates in holographic 3D compression. Accordingly, [21] applies Fresnelets as a combination of b-spline wavelets and Fresnel transform to compress the phase-shifting digital holograms. This combination demonstrates better compression performance in phase-shifting digital holograms [22, 23]. A combination of wavelets and Bandelet transform in a hierarchical form is suggested for holographic compression [24]. It boosts the compression rate in comparison to DCT-based compression methods and conventional wavelets. Viswanathan et al. use the Morlet wavelet transform to compress holographic images based on the viewer position [25]. In another research, Viswanathan et al. apply Gabor and Shannon wavelet transforms to propose a networked hologram adaptive codec [26]. Viswanathan et al. compare Gabor and Fresnelet-based wavelet in view-dependent hologram compression, where the Gabor wavelet is revealed to present better quality under similar conditions [27]. Blinder et al. use modulo wavelet transform for wrapped phase data in holograms [28]. Cheremkhin and Kurbatova present an optimized algorithm for compressing and storing 3D scenes such as holograms using a one-dimensional wavelet transform [29]. El Rhammad et al. propose a dictionary-based approach for color hologram compression based on a combination of Gabor wavelet and a matching pursuit scheme [30].

B. Frequency Domain Compression Methods

JPEG-based compressions are also evaluated in 3D images because of their applications to conventional images. It is one of the most applied image compression methods and is optimized in computational complexity and compression rate. Naughton et al. studied the quality and compression ratio of traditional 2D image codecs on digital holograms [31]. They use correlation as a quality metric and reveal that more than 90% of the cosine and Fourier components could be removed in 3D images without significant correlation loss. A JPEG2000-based codec has been suggested in [32] for coding some off-axis microscopy holograms. This codec extends the use of wavelet decomposition and directional wavelet transforms. Recent advances in applying JPEG to the area of 3D content-based image compression is also reviewed in [33]; additionally, the feasibility of using the JPEG standard on holographic images is evaluated.

C. Hybrid Compression Method

MPEG-4 is the first codec selected from this group. Darakis and Naughton, in [34], investigated the performance of the MPEG-4 codec in compressing holographic images. They found that conventional image and video codecs can also be applied to holograms, with the codecs showing an excellent compression performance in 2D images and often working well in 3D images. Sharabayko et al. implemented VP9 and high efficiency video codec (HEVC) on holographic images [35]. They demonstrated that HEVC provides a few better qualities in similar conditions than VP9. However, the performance is relatively the same in most cases.

Bernardo et al. evaluated the performance of some codecs in the holo plane and object plane [36]. They observed that H265 can outperform other compression methods in both planes. Peixeiro et al. evaluated the performance of the H265 codec for computer-generated holographic (CGH) images [15]. Besides, they presented a modified HEVC using an adapted transform that could achieve a better peak signal-to-noise ratio (PSNR) and bitrate than conventional HEVC in the CGH. Bernardo et al. compared the performances of H264, H265, MPEG2, and JPEG codecs. The authors confirmed that H265 is the most efficient scheme among all evaluated codecs [37]. Chen et al. explained full details of AV1 codec and compared this codec with VP9 and HEVC [38]. They revealed that performance of the AV1 codec is very close to H265 for compressing 3D holographic videos.

Corda et al. observed that HEVC and AV1 codecs present better results than other compression methods using the objective test metrics for holograms [39]. This result confirms the findings of the usual quality metrics used in previous research.

D. Other methods

This class includes all methods not included in previous categories. Seo et al. applied a combination of DCT, 3D scanning, segmentation, coefficient clustering, H264, and differential pulse code modulation to compress color holograms [40]. Tsang et al. compressed color holograms using a vector-based quantization method [41]. This method presents an excellent compression ratio, but is only implemented on Fresnel holograms. Senoh et al. suggested depth map coding for compression holograms in holographic TV systems. Real-time processing and low bandwidth are among their advantages [42].

Xing et al. proposed an adaptive vector lifting approach for compressing holographic data [43]. One of the advantages of this method is its applications in different types of holograms [43]. Modi et al. suggested a compression method based on 3D image estimation by collecting 2D planes and then storing the plane parameters instead of depth information [44]. In another research, several target holograms were encoded into pairs of front and rear phase distorting surfaces [45]. Challenges in holographic near-eye displays in real applications and effective methods for these types of displays have been considered in [46].

In light of this review, it can be stated that coding and compression methods in holographic images still requires extensive studies. Also, exploring the phase domain would be an excellent candidate for compression, given holograms' sensitivity to phase.

III. Proposed Method

Hologram codecs consist of encoding (compression) and decoding (decompression) steps. Each of these two steps commonly contains different blocks. Accordingly, the proposed encoder is depicted in Fig. 1.

A. Encoding

The goal of this step is to compress the hologram phase data. First, the hologram phase data are extracted. The extracted data is then compressed using the AV1 method with a user-defined quantization value and then decompressed (E1, E2). The quantization value is one of the parameters that can be tuned by the user, directly affecting the size of the output file and the decompressed holograms' quality. These two parts are similar to the standard AV1 method. After applying AV1 encoding to the hologram, the error is computed, i.e., the difference, between the E1 and E2 blocks input and output. In all modern compression methods, different compensation steps are used for error minimization. In a well-structured compression method, the final error and input image should be uncorrelated as much as possible. There, it is no possibility for further error compensation from the original image and its essential parts. Hence, the output image of AV1 is re-encoded by an AV1 encoder-decoder with a specified quantization value.

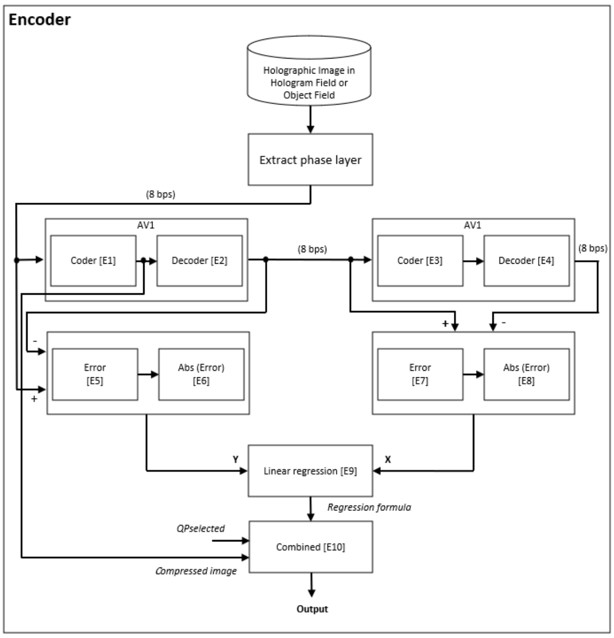

Fig. 1. Flowchart of the Encoding step of the proposed method.

This quantization value is pre-determined in the codec and is out of reach (E3, E4). This results in a new output image error (E7), where it is expected that E5 and E7 are fairly well-correlated, given the decoder structure used in this block (E3-E4), and its similarity to the previous structure (E1-E2). In the proposed method, E5 and E7 errors have equal signs; therefore, the error sign can be ignored. Accordingly, the absolute values of E5 and E7 are calculated and designated as E6 and E8, respectively. In brief, E6 represents the absolute error between the original image and the output image of the first AV1 block, i.e., E4. In contrast, E8 represents the absolute error between the reconstructed images of the first and the second AV1 blocks. In fact, the second encoding step error can be reconstructed ideally in decoder, so it can be used to find the first step error and compensate it without adding any extra data to the output file. These two values are then applied to a linear regression block (E9), where an approximately linear relationship is found between them. Since E2 and quantization value are known in the decoding step, the second AV1 block error (E7) and its absolute value (E8) can be created easily. The ability to generate these values in the decoder plays a crucial role in the proposed methods' efficiency. Nevertheless, the linear regression in E9 is estimated using the output of E8 as x-axis and the output of E6 as y-axis.

Briefly, the linear regression in E9 estimates the absolute value of the original error, i.e., E6, from E8. Adding the estimated original error to the image created in the AV1 output, E2, improves the output quality and reduces output error. The linear regression computed in E9 combines the user-selected quantization coefficient and image compressed in AV1 first decode-encoder (E2) to form the final output file (E10). Since only two linear regression coefficients and one quantization value ($QP_{selected}$) are added to the standard AV1 output file, the impact on the output file size is negligible and can be easily ignored.

B. Decoding

The original image should be extracted from the encoded output file with the highest quality in the decoding. Fig. 2 depicts the flowchart of decoding step. In the first block (D1), the received encoded file (E10) is split to standard AV1 compressed image (E2 output) using the regression formula (E9 output) and quantization coefficient of the second AV1 encoder-decoder block ($QP_{selected}$). In the D2 block, the compressed image is decompressed using the standard AV1 decoder. The output of this block is equivalent to the E2 output of the encoding step. The output image of D2 is again applied to an AV1 encoder-decoder (D3, D4) using the QP selected quantization coefficient extracted in the D1 block.

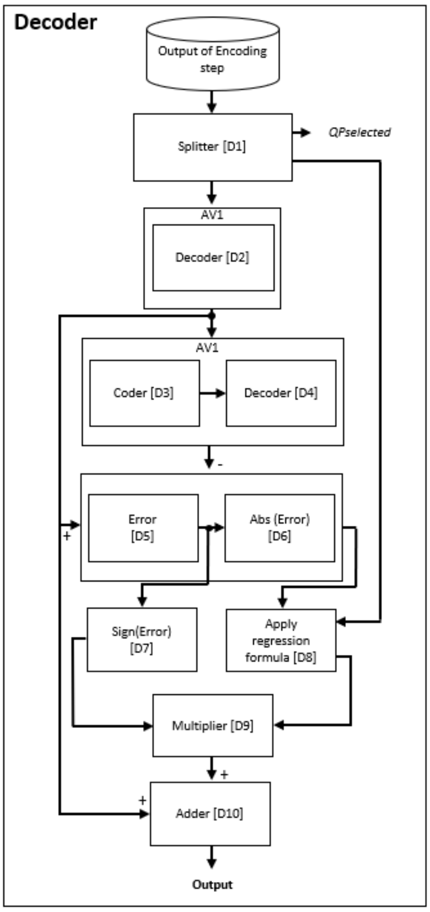

Fig. 2. Flowchart of the Decoding step of the proposed method.

The AV1 encoder-decoder (D3, D4) are precisely equivalent to the E3 and E4 blocks of the encoding step. In the D5 and D6 blocks, the error and its absolute value are calculated. This error is fully equivalent to the error generated in the E7 and E8 blocks of the encoding step. Consequently, the error sign is extracted in D7. Note that the error sign is equal to the sign of standard AV1 error, calculated in the E5 block in the encoding step.

The regression formula extracted from the input file is then applied to the absolute error (D6 output). If the linear relationship was ideal, the output would be exactly equal to the E6 output in the encoding step, the absolute error of standard AV1 compression. The error sign extracted at D7 is combined with the absolute error in the multiplication D9 block to compute an equivalent to the E5 error of the encoding step. Finally, the standard AV1 error, estimated in D9, is added to the standard AV1 codec output to compensate for the AV1 error with the minimum computational and storage load. Hence, the proposed method enhances the AV1 output under the same conditions as the standard AV1, and offers a better image quality at approximately the same storage requirement.

IV. Simulation Results

Here, the proposed method is compared againts conventional coding methods in holographic images to confirm its efficiency in maintaining quality and reducing required storage. Since the proposed method only alters the phase part, all comparisons are made on the phase part of holograms.

There are only a few standard benchmark holographic datasets for algorithm assessments. As a consequence, special attention should be given to the different imaging technologies when reporting the results. The proposed method was tested on two different datasets. The first dataset is the EmergIMg [14, 47], which contains a set of 10 holographic images of real recorded holograms. The second dataset is Interfere I, created by Peter Shelkens [33], which is part of the computer-generated holography (CGH) datasets, and therefore its five images are fundamentally different from the first one. Fig. 3 showns the 2D representation of the selected holograms.

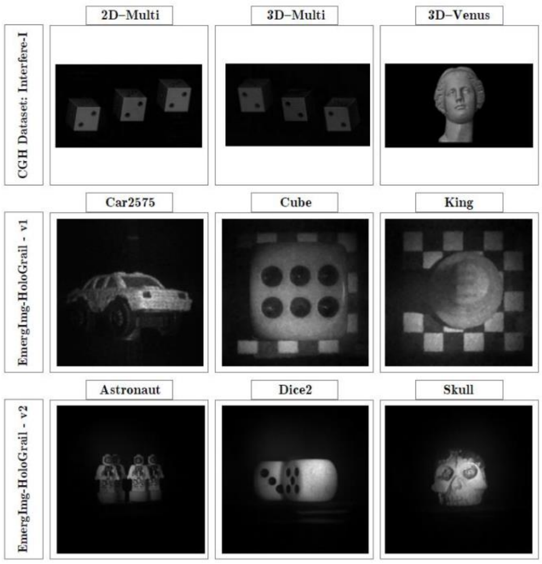

Fig. 3. 2D representation of the selected holograms.

As aforementioned, the proposed method is compared against various standard 3D image coding methods, mainly, JPEG2000 [48], H265 [49], AV1 [50] and VP9. For performance evaluation, the PSNR, SSIM, Bjøntegaard delta (BD)-PSNR and BD-Rate have been considered as recent quality measures in Holo images [16, 17, 51]. The objective quality evaluation methods such as [39, 52] are not usual in Holo images.

The proposed approach's implementation results on used datasets are presented in Figs. 4 to 7. These figures compare the values as to PSNR and SSIM obtained by the proposed method and the ones obtained by benchmarking codecs for the phase part of Astronaut hologram's holo on the object plane according to various bits per pixels (Bpp). Based on Figs. 4 to 7, one can confirm that the proposed method enhances PSNR and SSIM at quantization coefficients greater than 15 relatively to the other codecs under study. Among all codecs, the most significant improvement is found relatively to the VP9 codec.

The HEVC and AV1 codecs perform better than VP9 and JPEG2000 codecs. In particular, it can be deduced that the HEVC codec outperforms all conventional methods. Interestingly, the proposed method beats HEVC and AV1 in all scenarios. At quantization coefficients lower than 15, the codecs' results are almost equal due to the high output quality. The proposed codec can be applied to a wide range of holograms, both in the holo and object planes, for various compression ratios.

In addition, the BD-Rate and BD-PSNR based comparisons between the proposed method and AV1 are summarized in Tables I and II for holo and object planes. The results of Tables I and II unfolds that the proposed method outperforms AV1 up to 5.0 dB in terms of BD-PSNR while requiring 25.0133% less resource measured in the BD-Rate for the holo plane. These quantities are 4.7 dB and 28.5% for object plane, respectively. It is worth to mentioning that the obtained out-performance can be considered very significant since AV1 is already highly efficient, while the proposed method can beat it both in terms of compression rate and quality for all images from the used two different datasets. One of the immediate results that can be inferred from the data presented in those tables, is that the proposed method can present appropriate and relatively similar qualities for different holograms. That is, the performance of the proposed method is very stable on different holographic images. The relatively regular pattern of PSNR change with respect to Bpp in the proposed method allows predicting the quality from the required capacity. This can be considered as another advantage of the method.

To summarize, the proposed hybrid codec at high quantization values significantly outperforms all other benchmarking compression codecs. In addition, the feasibility of applying the proposed method to the challenging phase part for different types of holograms is one of the main strengths of the proposed method.

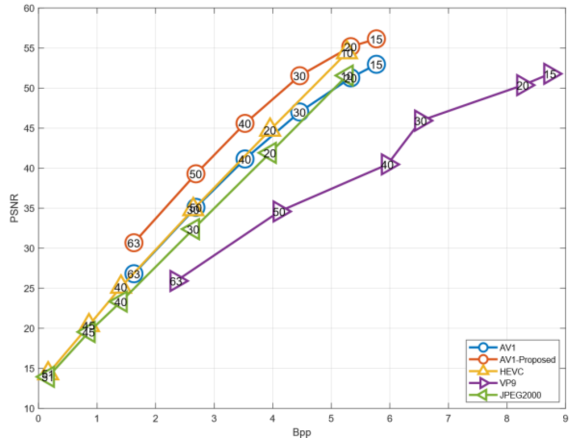

Fig. 4. PSNR vs Bpp in the phase part of holo plane in Astronaut.

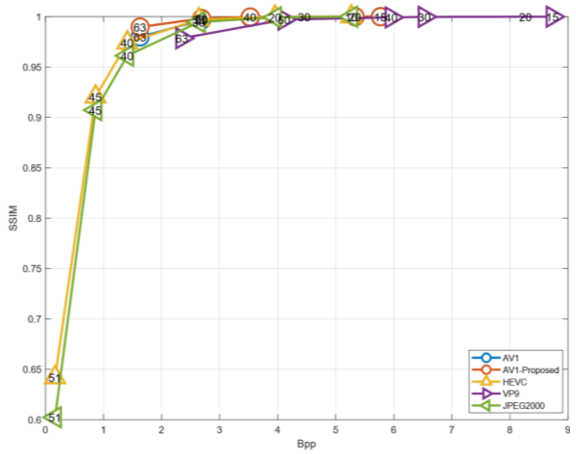

Fig. 5. SSIM vs Bpp in the phase part of holo plane in Astronaut.

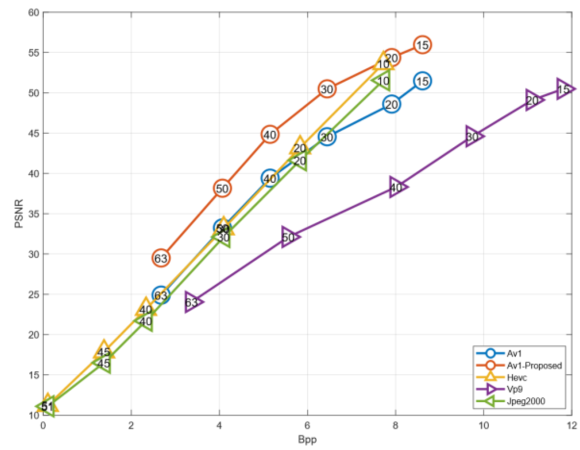

Fig. 6. PSNR vs Bpp in the phase part of object plane in Astronaut.

TABLE I. BD-PSNR AND BD-RATE OBTAINED BY THE PROPOSED METHOD ON THE OBJECT PLANE VS AV1.

3DMulti		2DMulti		3D-Venus	
BD-PSNR [dB]	**BD-Rate [%]**	**BD-PSNR [dB]**	**BD-Rate [%]**	**BD-PSNR [dB]**	**BD-Rate [%]**
4.88	-24.23	4.75	-25.70	4.85	-28.50
Cube		**Horse**		**Car2579**	
BD-PSNR [dB]	**BD-Rate [%]**	**BD-PSNR [db]**	**BD-Rate [%]**	**BD-PSNR [db]**	**BD-Rate [%]**
5.2	-19.92	5.00	-19.90	5.11	-20.06
Dice2		**Skull**		**Astronaut**	
BD-PSNR [dB]	**BD-Rate [%]**	**BD-PSNR [dB]**	**BD-Rate [%]**	**BD-PSNR [dB**	**BD-Rate [%]**
5.15	-20.18	5.23	-20.20	5.21	-20.21

TABLE II. BD-PSNR AND BD-RATE OBTAINED BY THE PROPOSED METHOD ON THE HOLO PLANE VS AV1.

3DMulti		2DMulti		3D-Venus	
BD-PSNR [dB]	**BD-Rate [%]**	**BD-PSNR [dB]**	**BD-Rate [%]**	**BD-PSNR [dB]**	**BD-Rate [%]**
4.85	-24.35	4.78	-25.01	4.77	-22.42
Cube		**Horse**		**Car2579**	
BD-PSNR [dB]	**BD-Rate [%]**	**BD-PSNR [db]**	**BD-Rate [%]**	**BD-PSNR [db]**	**BD-Rate [%]**
4.97	-19.73	4.96	-19.67	4.92	-20.65
Dice2		**Skull**		**Astronaut**	
BD-PSNR [dB]	**BD-Rate [%]**	**BD-PSNR [dB]**	**BD-Rate [%]**	**BD-PSNR [dB**	**BD-Rate [%]**
3.96	-17.70	3.99	-18.65	3.97	-17.75

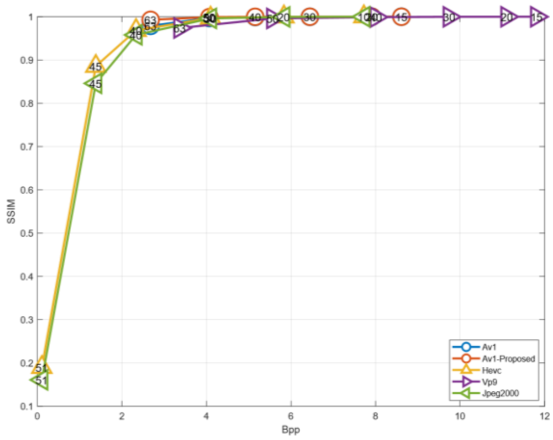

Fig. 7. SSIM vs Bpp on the phase part of the object plane as to Astronaut.

V. CONCLUSION

In this article, a modified AV1 method is proposed to improve the efficiency of phase compression of holographic images. The proposed method consists of several compensation steps, heterogeneous image resizing, and combinations of time-frequency space and geometrical methods. Through extensive simulations and comparisons, it was verified that the new method can estimate the nonlinear distortion in the output of the hologram phase part of the AV1 codec, with a minimal increase in output file size. It also significantly improves phase coding, particularly in high quantization coefficients. Other imperative advantages are its regular behavior for different quantization coefficients, and its applicability to different types of holographic images in both the holo and object planes. The comparison of the proposed method against different state-of-the-art codecs in 3D compression revealed that the proposed method can improve the quality up to 15% and 4% as to PSNR and SSIM, respectively. When considering the BD-PSNR and BD-Rate metrics, the proposed hybrid codec is highly promising, showing a remarkable improvement in-phase part of holograms for both the holo and object planes.

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