MCL-3D: a database for stereoscopic image quality assessment using 2D-image-plus-depth source

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Abstract.
A new stereoscopic image quality assessment database rendered using the 2D-image-plus-depth source, called MCL-3D, is described and the performance benchmarking of several known 2D and 3D image quality metrics using the MCL-3D database is presented in this work. Nine image-plus-depth sources are first selected, and a depth image-based rendering (DIBR) technique is used to render stereoscopic image pairs. Distortions applied to either the texture image or the depth image before stereoscopic image rendering include: Gaussian blur, additive white noise, down-sampling blur, JPEG and JPEG-2000 (JP2K) compression and transmission error. Furthermore, the distortion caused by imperfect rendering is also examined. The MCL-3D database contains 693 stereoscopic image pairs, where one third of them are of resolution \(1024 \times 728\) and two thirds are of resolution \(1920 \times 1080\). The pair-wise comparison was adopted in the subjective test for user friendliness, and the Mean Opinion Score (MOS) can be computed accordingly. Finally, we evaluate the performance of several 2D and 3D image quality metrics applied to MCL-3D. All texture images, depth images, rendered image pairs in MCL-3D and their MOS values obtained in the subjective test are available to the public (http://mcl.usc.edu/mcl-3d-database) for future research and development.

Keywords: stereoscopic images, 3D images, depth image based rendering, subjective quality, perceptual quality, image quality assessment, image quality database.

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1 Introduction

Stereoscopic image/video contents become popular nowadays. Since the multi-view image format\(^1\) is costly for visual communication, the 2D-image-plus-depth format\(^2\) is proposed as an alternative, where a texture image and its associated depth image are recorded at a view point simultaneously. For stereoscopic display, the depth image-based rendering (DIBR) technique is applied to the texture and depth images to generate the proper left- and right-views. The 2D-image-plus-depth format has a few advantages, including bandwidth efficiency, interactivity and 2D/3D video content switch, etc\(^3\). A 3D video coding standard, called MPEG-C part 3\(^4\), has been developed using
the Multi-View-plus-Depth (MVD) format. In this work, we address the visual quality assessment problem using the 2D-image-plus-depth source. With the DIBR technology, the stereoscopic images rendered and displayed on the stereoscopic screen rely on the quality of texture images, depth maps and the rendering technology. Since discomfort caused by watching stereoscopic images may go beyond annoying and lead to psychological dizziness, we cannot over-emphasize the importance of the stereoscopic image/video quality assessment problem.

We show the processing flow of a stereoscopic visual communication system with the DIBR technology in Fig. 1. At the encoder end, the texture and depth images captured at one viewpoint (or multiple viewpoints) are compressed and transmitted separately. At the decoder end, texture and depth maps are decoded and a pair of stereoscopic images can be rendered. In this work, we follow a similar process to build a stereoscopic image quality assessment database and consider a wide range of distortion types occurring in video capturing, compression, transmission and rendering. The resulting database is called MCL-3D.

![Fig 1](image)

**Fig 1** The processing flow of a stereoscopic visual communication system with the DIBR technology.

There are several publicly accessible stereoscopic image databases developed for the quality assessment purpose as listed in Table 1. Only symmetric distortions (i.e., the same distortion type and level) are applied to the left and right images in the LIVE Phase I database. Non-
symmetric distortions are considered in the LIVE Phase II database\(^5\) as a generalization. The IVC 3D database\(^7\) is similar to LIVE Phase I yet with a different set of source images. One common concern with these three databases is that the resolution of stereoscopic images is low. Images of higher resolution are adopted by the IVC DIBR\(^8\) and the EPFL databases.\(^9\) One unique feature of the EPFL database is that it examines the effect of different disparity values on the resulting visual quality so as to develop a guideline on disparity selection. A similar yet more delicate work is given in \([10]\), where the disparity effect on continuous video is analyzed so that some visual metrics can be fine-tuned for disparity selection in 3D films. The IVC DIBR database examined the visual quality of rendered stereoscopic pairs with various rendering mechanisms. However, no transmission distortion is considered. Furthermore, distortions were imposed on binocular images directly, which has a more restricted application constraint.

| Table 1 | Summary of 3D Image Databases |
|---------|------------------------------|
|         | LIVE\(_I\) | LIVE\(_II\) | IVC 3D | IVC DIBR | EPFL |
| Scenes  | 20         | 8           | 6      | 3        | 10   |
| Resolution | 640x360 | 640x360 | 512x448\(^1\) | 1024x768 | 1920x1080 |
| Distortion types | Blur, White noise, Fast fading, JPEG, JP2K | Blur, White noise, Fast fading | Blur, Holl filling | JPEG, JP2K |
| Distortion Levels | \(^{-2}\) | \(^{-3}\) | \(^{-4}\) | \(^{7}\) | \(^{10}\) |
| Total Num | 385 | 368 | 96 | 96 | 100 |

\(^1\) Image size is not identical in IVC 3D, 512x448 is the mean value provided in the corresponding paper.

\(^2\) Different distortion types have different levels in LIVE Phase I.

\(^3\) LIVE Phase II has complex level definitions for asymmetrical distortion types.

\(^4\) Different distortion types have different levels in IVC 3D database.

\(^5\) IVC DIBR database has 7 different hole filling algorithms, taken as 7 distortion levels.

\(^6\) 10 camera configurations, taken as 10 distortion levels.
In contrast, distortions are applied to either the texture image or the depth image before stereo-
oscopic image rendering in MCL-3D. The distortion types of consideration include: Gaussian
blur, additive white noise, down-sampling blur, JPEG and JPEG-2000 (JP2K) compression and
transmission error. The artifact caused by imperfect rendering is also considered. The pair-wise
comparison was adopted in the subjective test to be friendly to viewers, and the Mean Opinion
Score (MOS) was computed accordingly. All texture images, depth images, rendered image pairs
and their MOS values obtained from the subjective test in MCL-3D are available to the public
(http://mcl.usc.edu/mcl-3d-database/) for future research and development.

The rest of this paper is organized as follows. The source data, the DIBR rendering process
and distortions adopted by the MCL-3D database are detailed in Sec. 2. The human subject test
process is presented in Sec. 3. Then, we compare several existing 2D and 3D objective image
quality assessment methods against the MCL-3D database in Sec. 4. Finally, concluding remarks
and future work are given in Sec. 5.

2 Description of MCL-3D Database

2.1 Stereoscopic Image Pair Synthesis System

The stereoscopic image pair synthesis system used to create the MCL-3D database is shown in
Fig. 2, where characters $O$, $D$ and $R$ denote original input, distorted and rendered outputs, and
subscript characters $T$, $D$ and $V_L$ and $V_R$ denote the texture image, depth map, rendered left-
view and right-view, respectively. First, the original texture image and its associated depth map
of three views, denoted by $(O_{T1}, O_{D1})$, $(O_{T2}, O_{D2})$, and $(O_{T3}, O_{D3})$, are obtained by selecting
key frames from 3DVC test sequences and used as the input. Distortions of different types and
levels were introduced to either the texture image or the depth map, and distorted texture images or
depth maps are used as the input to the view synthesis reference software (VSRS)\textsuperscript{[2]} to render the distorted stereoscopic image pair. For the DIBR distortion, we take the original source $O_{T2}$ and $O_{D2}$ as the input, and use four different rendering algorithms to generate the stereoscopic image pair. The VSRS offers a near prefect stereoscopic image synthesis mechanism. If the original left- and right-views are given, the VSRS can output a near perfect rendered view in between. The rendered left-view and right-view using the original texture images and depth maps, denoted by $R_{VL}$ and $R_{VR}$, will be taken as the reference for further analysis.

![Fig 2](image-url) The block-diagram of the stereoscopic image pair synthesis system used to create the MCL-3D database.
2.2 Image and Depth Source

The quality of a database is highly dependent on reference images. The selected images should be representative and with sufficient diversity. The test sequences used in the 3DVC standard can be good candidates, which provide a few multi-view sequences associated with depth maps. We removed those of uncommon spatial resolution and/or with a camera calibration problem from this candidate set and, finally, selected nine of them as the reference images in the MCL-3D database. They are shown in Fig. 3.

![Reference images in the MCL-3D database.](image)

Fig 3 Reference images in the MCL-3D database.
2.3 Distortion Types and Levels

In a communication system that adopts the 3DVC coding standard, distortions may come from various stages such as image acquisition, compression, transmission and rendering. Gaussian blur and additive noise may occur in the acquisition stage. The image and the depth map may be downsampled to accommodate multiple display devices before compression. For efficient transmission, all images should be compressed, which leads to blockiness and compression blur. Transmission errors may occur in the transmission stage. A rendering algorithm will be adopted to render multiple views for display. Some of these distortions were investigated before as shown in Table 1. We include distortions of all above-mentioned cases in the MCL-3D database.

![Diagram of precessing flow and corresponding distorted part for each database](image)

**Fig 4** The entire precessing flow and the corresponding distorted part for each database

Based on the recommendations of ITU\textsuperscript{[13-15]} and VQEG\textsuperscript{[16-17]}, we consider five quality levels in subjective tests. The original reference stereoscopic images have the “excellent” quality while the other 4-level distorted images correspond to “very good”, “good”, “fair” and “poor”, respectively. The distortion caused by imperfect rendering has not been well studied before. Typically, only the mid-view image and its depth map are taken as the input, and a stereoscopic image pair is rendered using a hole filling technique. In our experiment, we take $O_{T2}$ and $O_{D2}$ as the input to generate the stereoscopic image pair. Distortion types are summarized in Table 2 and explained below.
Table 2 Distortion generation mechanisms and the associated level parameters.

| Distortion type        | Method                        | Level parameters                                      |
|------------------------|-------------------------------|-------------------------------------------------------|
| Gaussian blur          | 'GaussianBlur()' in OpenCV     | Standard deviation of the function kernel, 11, 21, 31 and 41 for 4 levels |
| Additive white noise   | 'randn()' in OpenCV            | Standard deviation parameter, 5, 17, 33 and 53 for 4 levels |
| Down-sampling blur     | 'resize()' in OpenCV           | Sampling ratio, 5, 8, 11 and 14 for 4 levels           |
| JPEG compression       | 'imencode()' in OpenCV         | Quality level parameter, 30, 12, 8 and 5 for 4 levels  |
| JPEG2000 compression   | Kakadu package                | Compression parameter, 200, 500, 900 and 1500 for 4 levels |
| Transmission error     | OpenJPEG lib with JPWL mode   | Different levels set by visual check                   |
| Rendering distortion   | Different hole filling algorithms | 4 algorithms corresponding to 4 cases                  |

- Gaussian Blur

Many parameters have to be calibrated\(^9\) during the acquisition of high quality stereoscopic images, wherein the focal length is a critical one. Texture images from any view will be blurred due to an improper focal length. Depth maps could be either acquired by equipments\(^18,19\) or estimated by depth estimation algorithms\(^20\). It was claimed by some researchers\(^2,8\) that the visual experience can be improved by applying some blur to the depth map before rendering. Its effectiveness can be studied using MCL-3D. We used ‘GaussianBlur()’ function in the OpenCV\(^21\) library to add the Gaussian blur effect and controlled distortion levels by varying the standard deviation parameter of the kernel. Their values were set to 11, 21, 31, 41 for four distortion levels.

- Additive White Noise

In digital image capturing systems, CMOS or CCD sensors are used to capture R/G/B color light intensities. The intensity is later transformed to the voltage and quantized to digital pixel values. Interference is ubiquitous in electronic circuits. It appears in form of additive white noise in the texture or depth image. The ‘randn()’ function in the OpenCV library...
was used to generate additive noise whose levels were controlled by selecting four standard deviation values (5, 17, 33 and 53).

- **Down-sampling Blur**
  The captured image may be down-sampled to fit a different spatial resolution requirement. The ‘resize()’ function in OpenCV is used for down-sampling and up-sampling. Four different down-sampling blur levels with a sampling ratio of 5, 8, 11 and 14 were included.

- **JPEG and JP2K Compression**
  We applied JPEG and JP2K compression to source images. For JPEG compression, we utilized the ‘imencode()’ function in OpenCV with four quality levels (30, 12, 8 and 5). For JP2K compression, we utilized the Kakadu package with four compression parameters (200, 500, 900 and 1500) for four distortion levels.

- **Transmission Error**
  We used the OpenJPEG library to encode source images and then applied unequal protection and error correction codes in the JPWL mode. Some bit errors were added to the compressed bitstreams. At the decoder side, the errors were partly corrected. With the assistance of protection methods, it is difficult to build a simple relationship between the bit-error rate and the visual quality of the decoded image. Thus, we used 80 seeds to generate a group of error-corrupted images and selected 4 from them to obtain 4 transmission error levels.

- **Rendering Distortion**
  Stereoscopic images were rendered based on the texture and the depth map images using the DIBR technology. Typical rendering errors include the black hole and the boundary blur,
which tend to appear with imperfect rendering techniques. We selected several representative ones, including DIBR without hole filling, DIBR with filtering, and DIBR with inpainting, and DIBR with hierarchical hole filling.

3 Subjective Test

For the subjective test, the test environment was set up according to the ITU recommendations and a pairwise comparison method was adopted. Testing results were verified after the subjective test procedure.

ITU and VQEG are two organizations working on the standardization of subjective test methods. Both of them have published recommendations on subjective test procedure for 2D images, 2D videos and stereoscopic images. They can be roughly classified into four groups according to score levels and stimulus numbers as shown in Table 3.

| Table 3 Recommendations for subjective test methods |
|---------------------------------|------------------|-----------------|
| **Single Stimulus**             | **Discrete Score** | **Continuous Score** |
| ACR, ACR-HR                     | SSCQE            |
| **Double Stimulus**             | DCR, DSIS, CCR, DSCQS, SAMVIQ |

1. ACR: Absolute Category Rating.
2. ACR-HR: Absolute Category Rating with Hidden Reference.
3. SSCQE: Single stimulus continuous quality evaluation.
4. DCR: Degradation category rating.
5. DSIS: Double Stimulus Impairment Scale.
6. CCR: Comparison Category Rating.
7. DSCS: Double Stimulus Comparison Scale.
8. DSCQS: Double Stimulus Continuous Quality Scale.
9. SAMVIQ: Subjective Assessment Methodology for Video Quality.

It was mentioned in [27] and [28] that the continuous scale score does not improve the precision of test results. For the ACR method, the same score may have a different meaning for a different assessor. Even for the same assessor, the rating criteria may vary along test time. For this reason, we focus on methods with double stimulus and discrete scores.
Furthermore, we adopted the pairwise comparison method in the MCL-3D database. The pairwise comparison method has solid mathematical foundation and is extensively used for resource ranking and recommendation systems. Generally speaking, two stereoscopic image pairs are viewed by an assessor simultaneously and, then, the assessor selects the preferred one so as to assign a point score. The point score of a stereo image pair will accumulate across multiple rounds of pairwise competition, and the final point score is properly normalized to yield the final opinion score for the same assessor. The opinion scores of multiple assessors are averaged to result in the final mean opinion score (MOS) for each stereoscopic image pair.

The subjective test environment is described below. The display equipment was 46.9” LG 47LW5600. Assessors were seated 3.2 meters away from the display screen as shown in Fig. 5. During the test, two stereoscopic image pairs were shown on the screen simultaneously. The images were resized to adapt to the display, and the gap between two images was padded with grey levels as specified in [14]. With pair-wise comparison, only the relative quality of the two pairs was annotated by the assessor and the resize operation had little affect on the final result.

Fig 5 Illustration of the subjective test environment.
We developed a program with a proper GUI interface to control the quality assessment process for each assessor. For each image set, the test time ranged from 12 to 15 minutes so as to comply with the recommendation in ITU-R Rec. BT.500. After the subjective test, we conducted a short interview with the assessor for their evaluation experience. The assessors were students from the University of Southern California in USA. Among the 270 assessors, there were 170 males (63%) and 100 females (37%). In order to investigate the score difference between experts and non-experts, we asked assessors about their familiarity on stereoscopic images. Among them, 34 (or 13%) were experts and 236 (or 87%) were non-experts. The age distribution of the assessors is given in Fig. 6.

Each assessor conducted the evaluation of all distorted images for one reference image in one test session. We collected 30 opinion scores for every distorted image pair. The subjective test results were further filtered by a screening process. In building the MCL-3D database, the highest 10% and the lowest 10% scores for each image were treated as outliers and discarded. The final
MOS was calculated as the mean of remaining 24 opinion scores. The recommended number of assessors is 15 by ITU and 24 by VQEG for images. Bose tested the number of assessors for the subjective test for synthesized 3D view and concluded that the minimum number is 32 for ACR and less than 24 for pairwise comparison. Thus, our MOS calculation does meet the requirements of all above recommendations.

A summary of the MCL-3D database is given in Table 4.

| Main Characters | MCL-3D database |
|-----------------|-----------------|
| Scenes          | 9               |
| Image resolution| 6 with 1920x1080 |
|                 | 3 with 1024x768 |
| Distortion types| Gaussian blur, Down-sampling blur, Additive white noise JPEG compression, JP2K compression, Transmission error, Rendering algorithm |
| Distortion levels| 4               |
| Total num of image pairs | 693             |
| Subjective test method | pair-wise comparison |
| No. of assessors | 270             |
| Scale of MOS    | 0...9           |

4 Performance Comparison of Objective Quality Indices

In this section, we compare the performance of several objective quality indices against the MCL-3D database.

4.1 Performance of 2D IQA Indices

There are quite a few 2D image quality assessment methods proposed in literature. Traditionally, image distortion indices focus on fidelity by measuring the exact difference between the dis-
torted and the reference images; e.g. the mean-squared error (MSE), the Peak Signal to Noise Ratio (PSNR), etc. The fidelity concept has been scrutinized and challenged by researchers recently. New image quality indices were proposed. Examples include the Noise Quality Measure (NQM), the Universal Quality Index (UQI), the Structural Similarity Index (SSIM), the Multiscale Similarity Index (MS-SSIM), the Feature Similarity Index, the visual information fidelity (VIF), the pixel-based VIF (VIFP), the visual signal-to-noise ratio (VSNR), the image fidelity criterion (IFC), PSNR-HVS and C4.

We applied these quality indices to the left- and the right-views of the stereoscopic image pairs and obtained their mean as the quality score. We conducted this test on the MCL-3D database as well as two other stereoscopic image databases; namely, LIVE Phase I and IVC 3D. The Pearson Correlation Coefficient (PCC), the Spearman rank order correlation coefficient (SROCC) and the mean-squared-error (MSE) between the MOS and the objective scores are shown in Table 5. We see that both the PCC and SROCC values of these indices are less than 90% against MCL-3D. There is certainly room for further improvement.

**Table 5** Performance comparison of 2D objective quality indices applied to MCL-3D, LIVE Phase I and IVC databases.

| Indices | MCL-3D | LIVE Phase I | IVC |
|---------|--------|--------------|-----|
|         | PCC | SROCC | MSE | PCC | SROCC | MSE | PCC | SROCC | MSE |
| C4      | 0.8683 | 0.8690 | 0.6452 | 0.9078 | 0.9144 | 0.0596 | 0.7874 | 0.7304 | 0.1700 |
| IFC     | 0.7395 | 0.7398 | 0.8757 | 0.5466 | 0.9071 | 0.0700 | 0.7051 | 0.6135 | 0.1955 |
| MS-SSIM | 0.8656 | 0.8763 | 0.6514 | 0.7382 | 0.6093 | 0.0972 | 0.7676 | 0.6919 | 0.1767 |
| NQM     | 0.8684 | 0.8694 | 0.6451 | 0.8349 | 0.8461 | 3.3030 | 0.6816 | 0.5973 | 0.2018 |
| PSNR_HVS | 0.8783 | 0.8857 | 0.6220 | 0.7563 | 0.8042 | 3.4906 | 0.7089 | 0.6374 | 0.1945 |
| PSNR    | 0.8320 | 0.8405 | 0.7218 | 0.6482 | 0.6529 | 3.9963 | 0.5843 | 0.5554 | 0.2238 |
| SSIM    | 0.7654 | 0.7834 | 0.8372 | 0.6977 | 0.6616 | 0.1391 | 0.6817 | 0.6478 | 0.2017 |
| UQI     | 0.7372 | 0.7551 | 0.8789 | 0.9007 | 0.8974 | 0.0750 | 0.5706 | 0.5244 | 0.2265 |
| VIFP    | 0.7770 | 0.7897 | 0.8188 | 0.8266 | 0.8681 | 0.0660 | 0.7355 | 0.6869 | 0.1868 |
| VIF     | 0.7762 | 0.7929 | 0.8202 | 0.8883 | 0.9002 | 0.0664 | 0.7971 | 0.7083 | 0.1665 |
| VSNR    | 0.8289 | 0.8370 | 0.7277 | 0.7317 | 0.7847 | 5.0763 | 0.6723 | 0.6110 | 0.2041 |
4.2 Performance of 3D IQA Indices

Several IQA indices have been developed to target at stereoscopic image pairs. Campisi\textsuperscript{40} conducted a preliminary test on the acuity difference between different eyes and found no apparent difference. Ryu\textsuperscript{41} proposed an extended version of the SSIM index based on a binocular model. Their index uses a fixed set of parameters and is not adaptive to asymmetric distortions. Ko\textsuperscript{42} introduced the structural distortion parameter (SDP), which varies according to different distortion types. The SDP was employed as a control parameter in a binocular perception model to provide robust QA results for both symmetric and asymmetric distortions. Gorley\textsuperscript{43} used the difference of relative contrast between the reference image pair and distorted image pair to derive the quality index. Benoit\textsuperscript{7} extracted the disparity maps from both the reference and the distorted image pairs, calculated the distortion between them, and integrated it with other factors to form the final quality index. Sazzad\textsuperscript{44} exploited the disparity map and performed several integration methods to derive the quality index.

We evaluated the following four indices against the MCL-3D, the LIVE Phase I, and the IVC databases:

- Method A\textsuperscript{41}
- Method B\textsuperscript{7}
- Method C\textsuperscript{40}
- Method D\textsuperscript{42}

The PCC, SROCC and MSE results are shown in Table 6. We see that these 3D IQA indices do not show much superiority over 2D IQA indices. How to derive a better 3D IQA index is still a
challenging problem.

### Table 6 Benchmarks of 3D quality assessment metrics

| Metric  | MCL-3D | PCC | SROCC | MSE | LIVE Phase I | PCC | SROCC | MSE | IVC | PCC | SROCC | MSE |
|---------|--------|-----|-------|-----|--------------|-----|-------|-----|-----|-----|-------|-----|
| Method A | 0.8419 | 0.8503 | 0.7020 | 0.6775 | 0.6075 | 0.1286 | 0.7579 | 0.6869 | 0.1799 |
| Method B | 0.7545 | 0.7672 | 0.8537 | 0.8174 | 0.8493 | 0.0930 | 0.2851 | 0.4916 | 0.2643 |
| Method C | 0.8683 | 0.8690 | 0.6452 | 0.9067 | 0.9133 | 0.0600 | 0.7873 | 0.7295 | 0.1700 |
| Method D | 0.8910 | 0.8880 | 0.6055 | 0.9080 | 0.9050 | 6.8870 | 0.8410 | 0.8030 | 11.1200 |

### 5 Conclusion and Future Work

In this work, a detailed description of a stereoscopic image quality assessment database called MCL-3D was given, and the performance benchmarking of several known 2D and 3D image quality metrics using the MCL-3D database were presented. Distortions applied to the texture image or the depth image before stereoscopic image rendering include: Gaussian blur, additive white noise, down-sampling blur, JPEG and JPEG-2000 (JP2K) compression and transmission error. Furthermore, we evaluated the performance of several 2D and 3D image quality metrics applied to MCL-3D. The MCL-3D database is available to the public for future research and development.

Based on the experimental results, we see that none of the existing objective quality metrics can provide satisfactory performance for several stereoscopic image quality databases, including MCL-3D. It is still an open problem to design a good objective quality method for 3D images. The learning-based methodology in [45] and [46] offers an effective solution to the 2D image quality assessment problem. We currently focus on the design of a good stereoscopic image quality metric along the same direction.
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