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TECHNICAL REPORT

colour inside

3D display devices –
Part 41-1: Holographic display – General information

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IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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FOREWORD

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IEC TR 62629-41-1, which is a technical report, has been prepared by IEC technical committee 110: Electronic displays.

The text of this technical report is based on the following documents:

Draft TR	Report on voting
110/1019/DTR	110/1066/RVDTR

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62629 series, published under the general title *3D display devices*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
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- replaced by a revised edition, or
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INTRODUCTION

This document is intended to gather technical information on holographic displays and to identify optical measurement items that would be required to characterize their performance.

3D DISPLAY DEVICES –

Part 41-1: Holographic display – General information

1 Scope

This part of IEC 62629 provides general information for the standardization of holographic displays.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
holographic display
three-dimensional display that generates light converging to each point of a three-dimensional image in space by light diffraction

3.1.2
complex amplitude
complex value representing the amplitude and phase as the light wave

3.1.3
wavefront
locus of spatial points that share the same phase of the light wave

3.2 Abbreviated terms

EOTF	electro-optical transfer function
FOV	field of view
FWHM	full width at half maximum
MTF	modulation transfer function
NA	numerical aperture
ROI	region of interest
SBP	space bandwidth product
SLM	spatial light modulator

4 Holographic display technologies

4.1 General

Holographic displays are considered as one of the promising displays that can present three-dimensional images with a natural sense of depth. Despite their potential advantages, requirements for high performance optical devices, especially spatial light modulators, and real-time computational power have delayed their development and commercialization. Recent advances on those optical devices and newly emerging potential applications, including augmented reality eyewear displays, vehicle head-up displays, and table-top displays, however, are stimulating active research and development activities in academia and industry. As of 2017, not only the research institutes but also many major companies [1 to 4][1] are developing holographic display techniques in various applications to prepare for their commercialization.

The properties of the holographic displays are largely different from other three-dimensional displays due to the fundamental difference in the image forming principle and thus standards on those three-dimensional displays cannot be applied to the holographic displays. Existing standards on holograms, for example ISO 17901-1 [5] and ISO 17901-2 [6], focus on the recording of analogue static holograms and the diffraction efficiency of their reconstructions and thus they do not cover the display aspect of the holographic displays.

A holographic display can be defined in different ways, for example:

1) display that generates light converging to each point of a three-dimensional image in space by light diffraction (see 3.1.1; this is the definition in a wide sense); or
2) display that generates a wavefront converging to each point of the three-dimensional images (this is the definition in a strict sense).

In the wide sense meaning, the holographic display includes a holographic stereogram that reconstructs different views of three-dimensional images while the strict sense meaning only includes displays that reconstruct the complex amplitude of the three-dimensional images in such a way that an individual image point is formed by the converging wavefront. The difference between the holographic stereogram and the holographic display in the strict meaning can be found in the continuity of the wavefront for each image point as illustrated in Figure 1. In the case of the holographic stereogram, the wavefront converging at the three-dimensional image point is continuous only piecewise while it is fully continuous in the holographic display in the strict sense. Since the wavefront is continuous only piecewise, the holographic stereogram can also be considered as a light field display that reconstructs light rays. However, this document covers both holographic display types as they share many optical characteristics in common.

[1] Numbers in square brackets refer to the Bibliography.

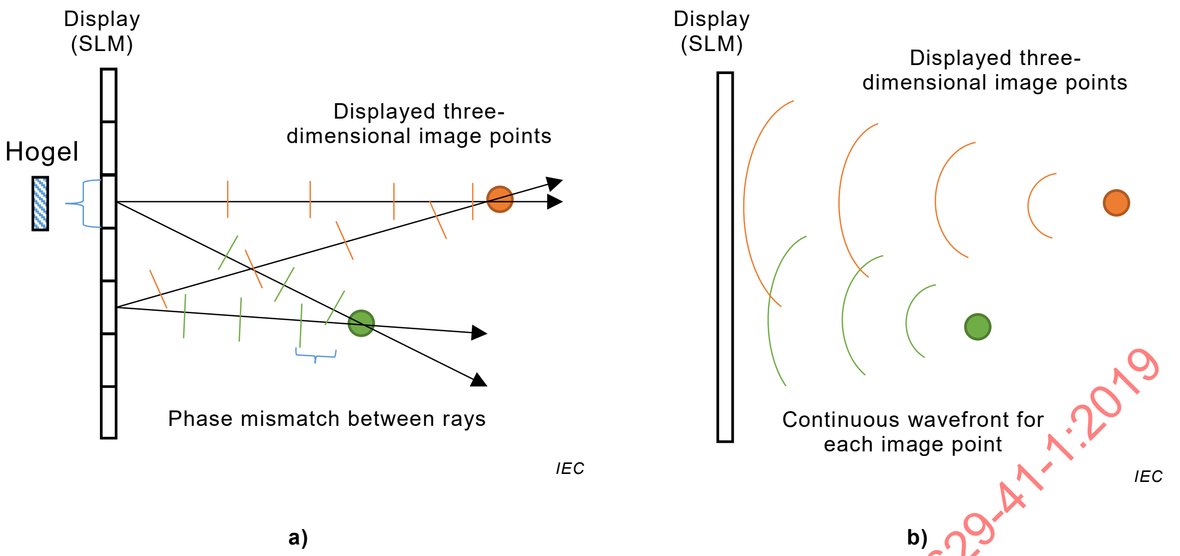

Figure 1 – Holographic stereogram (a) and holographic display in a strict sense (b)

The characteristics that distinguish holographic displays from other autostereoscopic three-dimensional displays are as follows:

- the light source is coherent or at least partially coherent with limited linewidth;
- light modulated by an SLM is diffracted to form three-dimensional images, and this diffracted light is captured by the user's eye;
- the modulating pattern loaded to the SLM is not a single view or a combination of multiple views of a three-dimensional image, but an encoded pattern to diffract the incident coherent light to the desired directions. It can be the interference pattern between the incident light and the complex amplitude of the three-dimensional image, the phase pattern of the complex amplitude, or other patterns depending on the modulation type of the SLM and the encoding technique used.

Displays that are sometimes called "holographic displays" but are not considered in this document are:

– displays that use a static hologram to merely control the light path from the usual two-dimensional displays such as LCDs and OLEDs. Eyewear displays using holographic optical elements or diffractive optical elements are examples. In this case, the image is not a three-dimensional but a flat two-dimensional one. The light diffraction does not contribute to the formation of the three-dimensional image but is only involved in the control of the light path from the display to the user's eye. Autostereoscopic three-dimensional displays based on directional backlight implemented using pixelwise grating are not included in this document because the grating is a fixed element and does not contain information on the image;

– displays that form a real or virtual image of a display panel by using a partially reflecting mirror or imaging optics so that the display panel looks as if it is floating in space. In this case, the floating image is still two-dimensional;

– displays that focus a high power laser beam at a designated position in space to create laser plasma excitation with spontaneous emission. These types of displays can use holographic display techniques to create multiple focal spots in space simultaneously. However, these displays are not considered in this document because the diffracted light is not captured by the user's eye but the secondary emission from the laser plasma is captured, giving optical characteristics of the displayed images very different from those of the holographic displays covered in this document;

– displays that project diffracted light from the SLM to a diffusing screen, presenting a large two-dimensional image on the screen. These types of displays are classified into laser projection displays which are covered in other documents.

4.2 Classification

As shown in Figure 2, holographic displays can be classified by considering the following factors:

- parallax provided (parallax that can be observed from the reconstructed three-dimensional images);
- wavefront continuity.

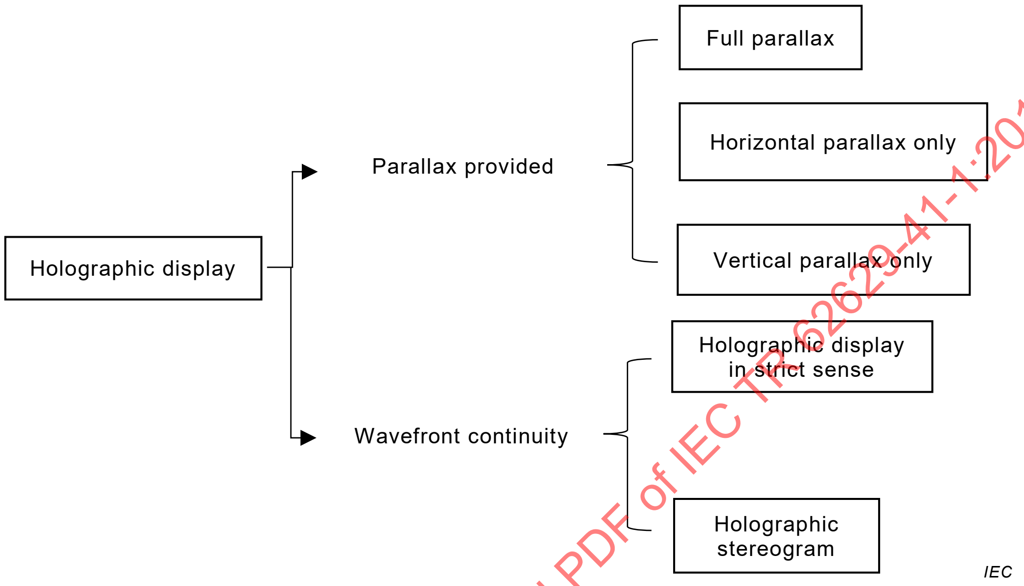

Figure 2 – Holographic display classification

4.3 Principles

4.3.1 Complex amplitude of three-dimensional image

The light emanating from or reflected from three-dimensional objects is a wave governed by a wave equation and it can be represented by a real valued function $u(x, y, z; t)$ where (x, y, z) is the position in three-dimensional space and t is time [7 to 9]. In a monochromatic wave case of a wavelength λ, the wave representation can be simplified to

$$u(x,y,z,t) = a(x,y,z)\cos\left(2\pi\nu t + \varphi(x,y,z)\right) = Re\left[U(x,y,z)e^{j2\pi\nu t}\right] \quad (1)$$

where

ν is a temporal frequency of the light oscillation given by $\nu = c / \lambda$ with light wave velocity c;

Re[] is an operator giving the real part of the input complex value;

$U(x, y, z)$ is a complex valued function containing the information of the amplitude $a(x, y, z)$ and phase $\varphi(x, y, z)$ of the light oscillation at every position in the three-dimensional space. Because the light propagation through free space is linear, the temporal frequency does not change, and thus $U(x, y, z)$ is sufficient to fully represent the wave in the monochromatic case. This $U(x, y, z)$ is usually called "complex amplitude" of the light with amplitude $|U(x, y, z)| = a(x, y, z)$, and phase $\angle U(x, y, z) = \varphi(x,y,z)$. The locus of the point having the same phase $\angle U(x, y, z)$ is called wavefront.

The complex amplitude $U(x, y, z)$ has three positional variables but it is not an arbitrary function with three degrees of freedom. Because the wave $u(x, y, z, t)$ needs to satisfy the wave equation, the complex amplitude $U(x, y, z)$ also needs to satisfy the corresponding differential equation, i.e. Helmholtz's equation. Therefore, the boundary condition in a certain plane, for example $U(x, y, z = 0)$, determines the complex amplitude in full three-dimensional space $U(x, y, z)$. Holographic displays optically create $U(x, y, z = 0)$ using an SLM to reproduce $U(x, y, z)$ corresponding to the desired three-dimensional images.

The complex amplitude in the SLM plane $U(x, y, z = 0)$ that corresponds to a three-dimensional image can be calculated using various methods which are usually called computer generated holography. One simple example is to represent the three-dimensional image using point cloud and add the complex amplitude terms of individual three-dimensional image point as follows:

$$U(x,y,z=0)=\sum_{m} a_{\mathrm{m}} e^{j\theta_{\mathrm{m}}} \exp\left[-j\frac{2\pi}{\lambda} r_{\mathrm{m}}\right] \quad (2)$$

where a_{m} and θ_{m} are the amplitude and phase of the m^{th} image point and r_{m} is the distance between the m^{th} image point and $(x, y, z = 0)$.

The above discussion is mainly on the case of the monochromatic wave. In order to display full colour images, three complex amplitudes corresponding to the R/G/B wavelength need to be created optically.

4.3.2 Reconstruction of complex amplitude with an SLM

Holographic displays reconstruct the complex amplitude in a plane $U(x, y, z = 0)$ using an SLM. The SLM is an optical device that can modulate the amplitude and/or phase of the incident light spatially. The SLM ideal for holographic displays is a complex modulating SLM that can modulate amplitude and phase at every position in the SLM plane with sufficient spatial resolution and quantization levels in phase and amplitude. Most of the currently available SLMs, however, have a limited modulation type, i.e. amplitude only or phase only, limited spatial resolution, and limited quantization levels in phase and amplitude, causing limitations on the reconstruction of the complex amplitude $U(x, y, z = 0)$. The consequence of the limited modulation of the SLM includes the generation of unwanted waves such DC and conjugate waves, limited FOV and range of viewing directions, and additional noises in the reconstruction.

In order to cope with a limited amplitude-only or phase-only modulation type of SLM, holographic displays usually ‘encode’ the target complex amplitude $U(x, y, z = 0)$ for the preparation of the modulation data fed to the SLM. Numerical interference, Buckhardt encoding, single-side-band encodings are a few examples of the encoding techniques for the amplitude-only SLMs and double-phase encoding is an example of the encoding techniques for the phase-only SLMs.

It should be noted that there are on-going efforts to develop a "complex modulating SLM". The usual approach is to stack an amplitude-only SLM and a phase-only SLM, and to realize simultaneous modulation of the amplitude and phase at each pixel of the SLM.

4.3.3 Spatial and temporal multiplexing of the SLM

The complex amplitude $U(x, y, z = 0)$ that needs to be reconstructed by the SLM has a huge amount of information. The amount of information in the complex amplitude can be represented by its space bandwidth product (SBP) which is the product of the spatial size and the spatial bandwidth of the complex amplitude $U(x, y, z = 0)$. This SBP translates into the product of the spatial size and the angular viewing direction range of the reconstructed three-dimensional images of the holographic displays. Since the SBPs supported by the currently available SLMs are much smaller than required, the holographic reconstruction of the three-dimensional images usually has an insufficient angular viewing direction range and spatial size.

In order to enhance the viewing direction range and the size of the reconstruction, spatial or temporal multiplexing of the SLM can be applied to holographic displays. The spatial or temporal multiplexing of the SLM increases the total amount of the SBP in a unit time, and thus it contributes to an increase of the image size, the angular viewing direction range, or both depending on the optical configurations. Figure 3 shows some examples of those approaches.

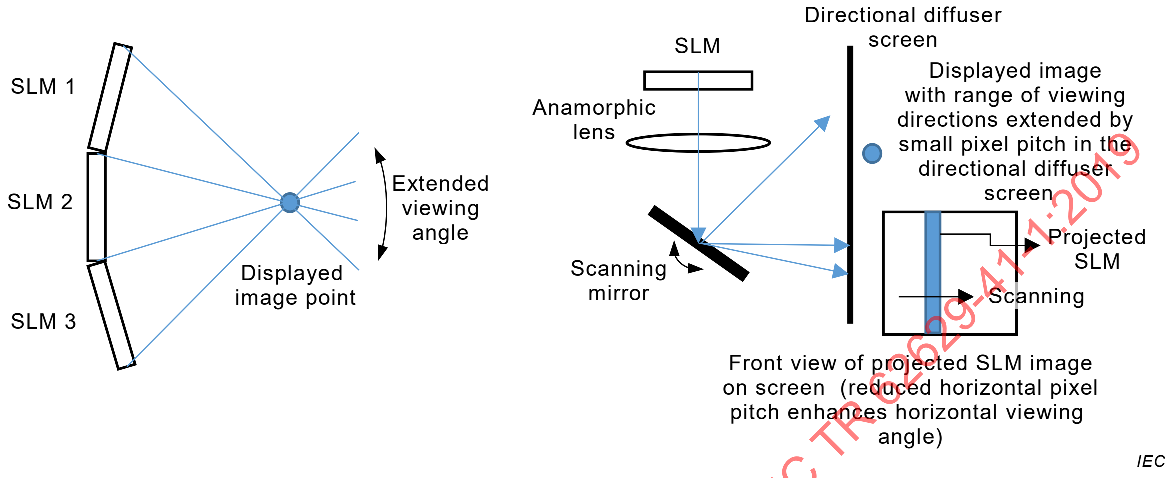

Figure 3 – Spatial and temporal multiplexing of SLM

4.3.4 Viewing-window-type holographic display

Some holographic displays form a viewing window where the user's eye should be located. As shown in Figure 4, a field lens converges the light diffracted from each part of the SLM , creating a window. The eye located in the window can see the diffracted light from all parts of the SLM, and thus the reconstruction size is the same as the size of the SLM itself. In this configuration, the viewing window size and its location would be more appropriate than the angular range of the viewing directions in describing the optical performance of this type of holographic display.

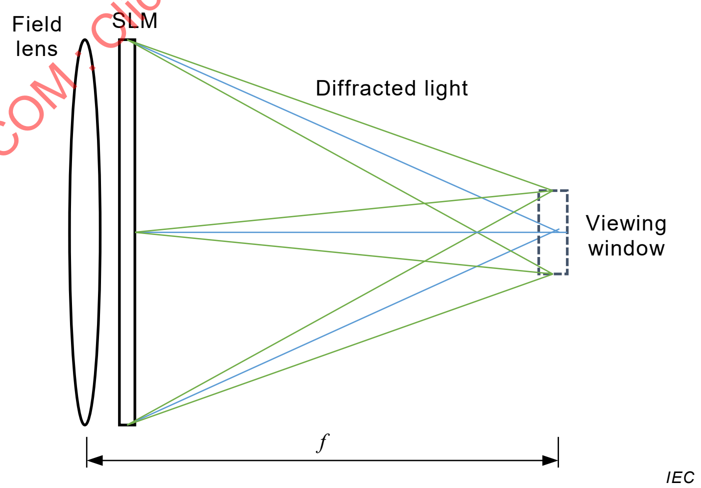

Figure 4 – Viewing-window-type holographic display

4.3.5 Holographic stereogram

The holographic stereogram is based on the same light diffraction as the holographic displays in the strict sense meaning. But the holographic stereogram is different in the sense that it reconstructs not a continuous converging wavefront to each three-dimensional image point but a collection of converging light rays. The phase relationship between the converging light rays can be random, and thus the wavefront continuity is maintained only within the spatial extent of an individual ray.

The holographic stereogram can be implemented in different ways and Figure 1(a) shows one possible configuration. In this configuration, the SLM area is divided into many sub-areas which are called "hogels". Each hogel is responsible for the reconstruction of the light rays that start from the hogel area, i.e. the "view" of the three-dimensional image at the hogel position. In order to reproduce those light rays, each hogel contains the encoded data of the complex amplitude of the light rays which can be obtained by approximating each light ray to a plane wave with a random phase.

5 Performance characteristics and specifications

5.1 General

The performance characteristics and specifications for holographic displays include not only optical performance, but also mechanical and electrical performance. This document mainly focuses on the optical performance. Specific measurement methods for these characteristics which are only partially covered in Annex A, need to consider the unique features of the holographic displays like the use of spectrally narrow coherent light sources. In this regard, other related standards, for example IEC 62906-5-1 [10], can be considered in the future development of the measurement methods for holographic displays.

5.2 Optical performance

5.2.1 Items related to effective resolution

In holographic displays, the effective resolution of the reconstructed three-dimensional images can be represented using the lateral/axial spot size and the MTF.

The spot size of the reconstruction is mainly determined by the NA. In optical imaging, the lateral spot size Δx and the axial spot size Δz are given by

$$\Delta x = \frac{\lambda}{2NA}, \quad \Delta z = \frac{\lambda}{NA^2} \qquad (3)$$

where NA is given by $D_e/2f_e$ where D_e is the exit pupil size and f_e is the axial distance of the image point from the exit pupil plane. In holographic displays, the effective exit pupil size of a given image point is given by different parameters of the SLM according to the optical configuration of the holographic display. For example, in the configuration shown in Figure 5 where the SLM itself is the exit pupil, the effective NA is given by $\lambda/2p$ where p is the pixel pitch of the SLM because the maximum diffraction angle θ that can be achieved by the SLM without aliasing is given by $\sin^{-1}(\lambda/2p)$.

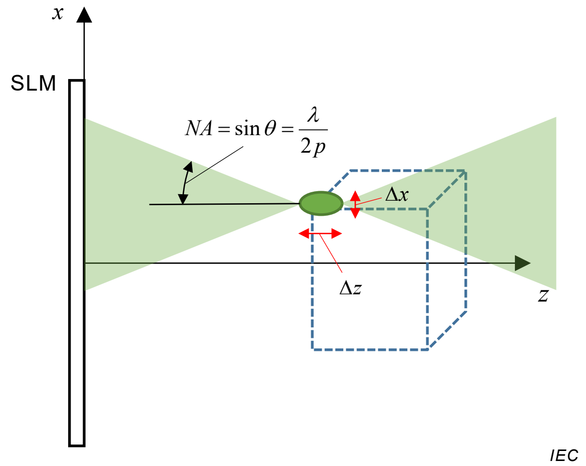

Figure 5 – Spot size

It should be noted that in case of a quasi-coherent light source, the spot will be further blurred because every monochromatic component within the linewidth of the light source will create the spot at slightly different lateral and axial positions.

The measurement items related to effective resolution include:

- lateral and axial spot size and its distribution within the image volume,
- MTF within the image volume.

5.2.2 Items related to speckle and other noise

Speckle is a grain-shaped noise in the reconstruction caused by the coherency of the light. As shown in Figure 6, the human eye has limited resolving power, and thus complex amplitude within an extended area in the reconstructed image surface, which is called the circle of confusion, is added for each point in the eye retina. If the reconstructed image surface has random phase distribution, this addition will result in random fluctuation of the intensity which is perceived as the speckle noise.

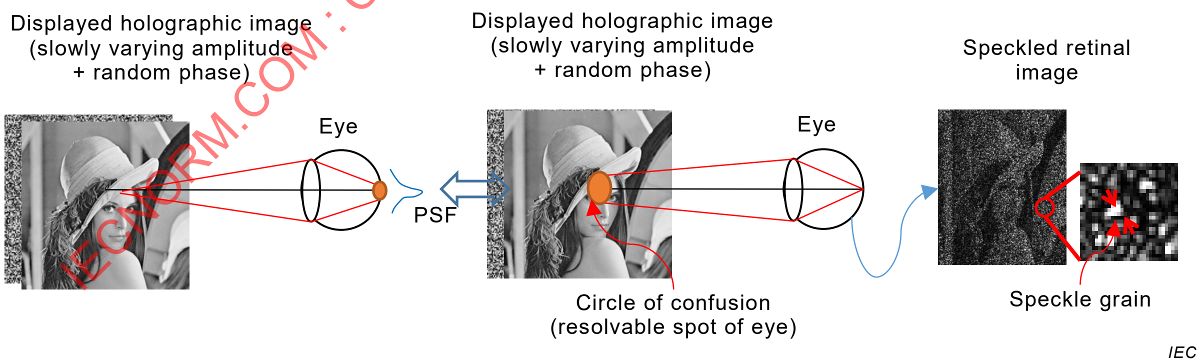

Figure 6 – Speckle noise

This speckle noise is a common phenomenon in displays using a coherent light source including laser projection displays. However, the speckle noise of the holographic displays may need to be treated differently because the phase distribution on the reconstructed image surface can be controlled by the holographic contents, there is no physical diffusing screen where the two-dimensional image is projected, and the speckle size and the speckle contrast can be dependent on the axial position of the image point within the reconstructed three-dimensional image volume.

In addition to the speckle, there are other noises in the holographic displays. The noise caused by the non-ideal modulation of the SLM is one example.

The measurement items related to speckle and other noises include:

- monochromatic speckle contrast, colour speckle contrast, speckle grain size,
- background noise.

5.2.3 Items related to distortion and chromatic aberration

In holographic displays, the image is aerial in the three-dimensional space and thus various aberrations of the optical components of the holographic display can degrade the image quality. The distortion of the displayed images is one example. The position where an image point is actually displayed can deviate from the designated position in three-dimensional space. This deviation should be measured both in the lateral and axial directions. The deviation also needs to be measured for image points at different three-dimensional positions to quantify its spatial variation.

The chromatic difference of the distortion is also important as it will separate the position of the reconstructed image point for different colours, significantly affecting the accommodative response of the eye.

The measurement items related to distortion include:

- lateral and axial deviation of the image point,
- chromatic position difference of the image point.

5.2.4 Items related to angular viewing direction range and viewing window

The angular viewing direction range or the viewing window size can be roughly defined by the angular or spatial range where full three-dimensional images within the designated FOV are observed. In case of the viewing-window-type holographic displays shown in Figure 4, the maximum diffraction angle of the SLM determines the viewing window size and it is given by $f\lambda$ / $2p$, where f is the focal length of the field lens which is the same as the axial distance of the viewing window from the lens.

The measurement items related to the angular range of the viewing directions include:

- angular range of the viewing directions,
- lateral size and position of viewing window.

5.2.5 Items related to image volume

Holographic displays create optical images of a three-dimensional scene. Therefore the image volume where the three-dimensional images can be displayed needs to be defined and measured. The exact definition of the image volume is an item that requires much discussion but it might be divided into lateral size, i.e. FOV, and axial size, i.e. depth range.

The FOV of holographic displays is the angular extent of the displayed three-dimensional images measured from the eye position. Caution is required in the measurement of the FOV, because the reconstructed images of the holographic displays are distributed in three-dimensional space and not in a two-dimensional plane.

The depth range of the holographic displays can be defined by the axial range where the three-dimensional image point has a tolerable spot size. Regardless of the exact definition, the general factors affecting the depth range include the image space NA and the coherency (or coherent length) of the light source. In the case of a holographic stereogram, the angular resolution of the reconstructed light rays also affects the depth resolution.

The measurement items related to image volume include:

- image volume,
- FOV,
- depth range.

5.2.6 Items related to chromaticity and luminance

As one of the most widely used light sources for holographic display systems, lasers provide not only a high coherency property but also an excellent wide colour gamut. However, due to the characteristics of the laser and optical reproduction process of a three-dimensional image, a variety of noises affects the holographic display technology. Such noises cause visual artefacts that degrade the quality of the chromatic information reconstructed by holographic methods. They include the aforementioned noises such as colour speckle, random phase, SLM modulation error, and chromatic aberration. In this chromatically noisy environment, it is observed that the spots to be reconstructed are easily overlapped with neighbouring noisy spots and noises and deteriorate not only the resolution but also the colour quality. In particular, there is not only the decrease of contrast but also the decrease of chroma because of the additive colour mixture of light.

In addition, since holography is based on light diffraction and grating, there is a drawback that the brightness of the three-dimensional image reconstructed by the holographic display is reduced because of the limited diffraction efficiency and the optical loss caused by a series of optical components in the holographic display system. Therefore, it is required that sufficient luminance and contrast performance be achieved as a display for bright and clear three-dimensional image reproduction.

The measurement items related to colour include:

- colour gamut,
- chromaticity difference,
- RGB EOTF,
- luminance.

Annex A
(informative)

Measurement of three-dimensional spot size, MTF and colour gamut

A.1 Three-dimensional spot size

Figure A.1 shows an example of the measurement equipment for a three-dimensional spot size [11]. A 4-f system is used to select the angular range required for the display. Fourier lenses should have NA sufficiently larger than the diffraction angle of the holographic display. Fourier lenses should have negligible aberration. Acceptance angle and depth are controlled by two apertures at the focal lengths of the Fourier lenses.

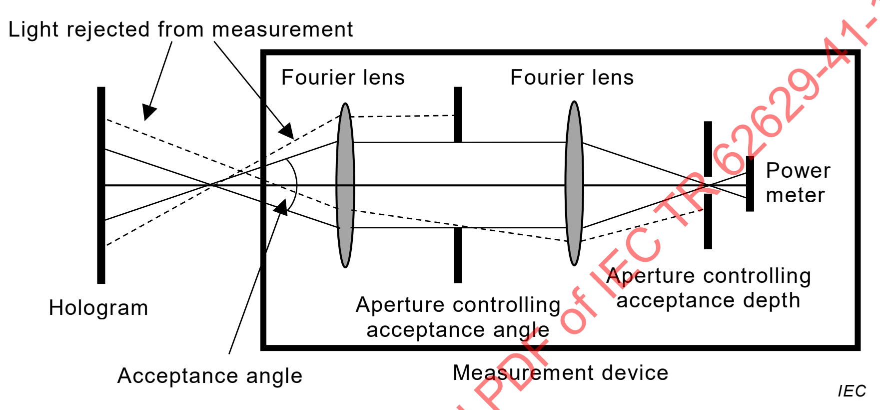

Figure A.1 – Measurement equipment of the three-dimensional spot size

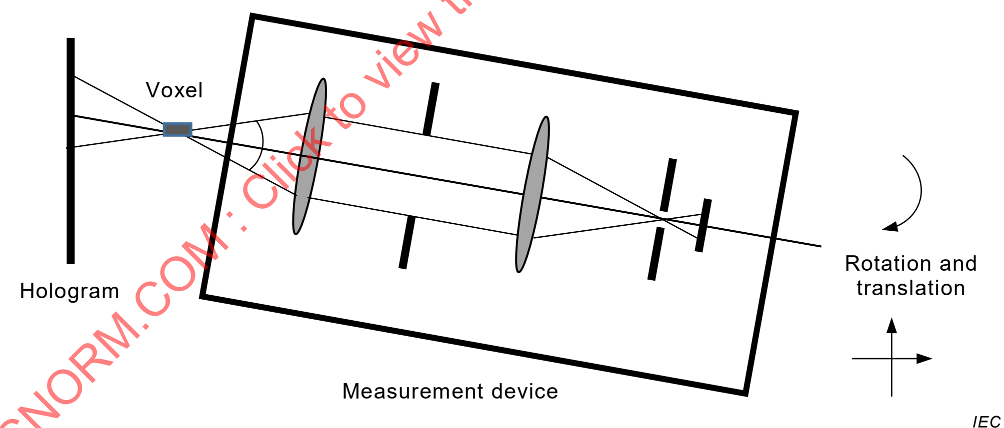

Figure A.2 – Measuring procedure of the three-dimensional spot size

Measurement can be done with the following procedure:

a) 3 x 3 x 3 or 5 x 5 x 5 voxels are measured,

b) the acceptance angle is set to be smaller than the diffraction angle to block high spatial frequency noise,

c) the radius a' of the acceptance depth controlling the aperture is set to be $a' = \lambda_o f / 2a$

where

λ_o is the center wavelength,

f is the focal length of the Fourier lens

a is the radius of the acceptance angle controlling aperture,

d) the measurement device is aligned in parallel with the central wave vector of the voxel as shown in Figure A.2,

e) the power distribution is measured while translating the measurement device in the x, y, and z directions,

f) the voxel's central position and the size are determined by the central position and the FWHM of the distribution.

A.2 MTF

An example of the measured MTF of a holographic display is given in Annex A. Figure A.3 shows the setup and the captured images.

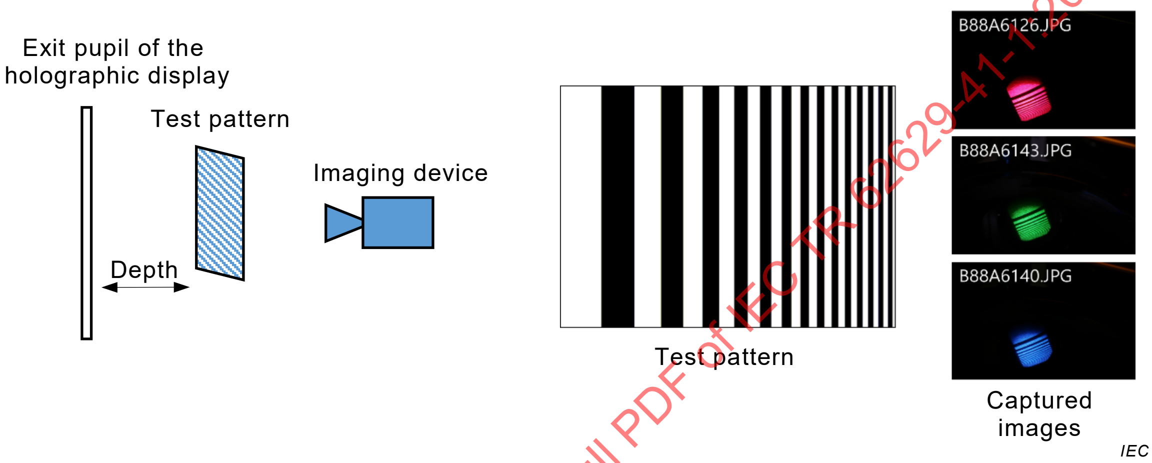

Figure A.3 – Measuring setup and captured images

The ROI in the captured images is then extracted and rectified as shown in Figure A.4.

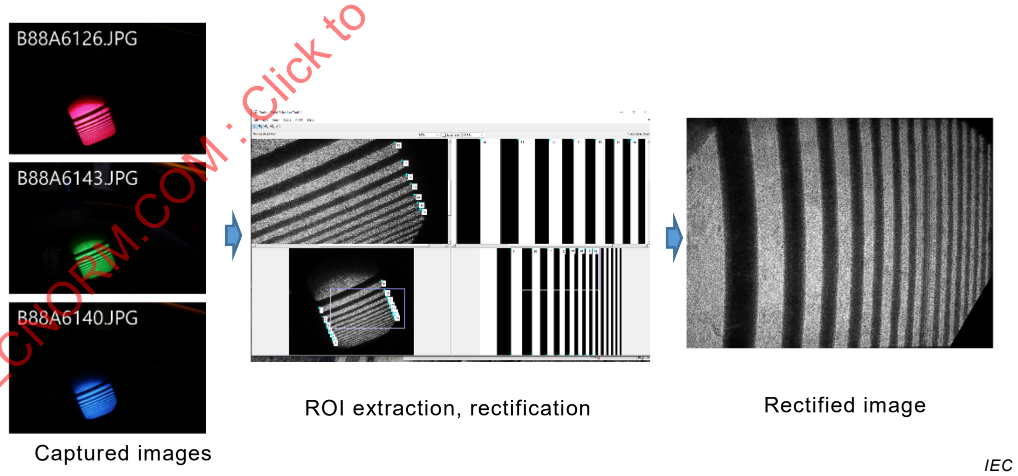

Figure A.4 – ROI extraction and rectification

In order to suppress the effect of the speckle noise, the cross-sections of the rectified images are averaged as shown in Figure A.5 and the modulation depth is measured as shown in Figure A.6.